LEGAL ASPECTS OF AIRPORT NOISE AND SONIC BOOM

PART II

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Part II: THE SONIC BOOM

Chapter I: CAUSES AND CHARACTERISTICS

Certainly one of the most controversial aspects of the use of supersonic transports in commercial aviation is the sonic boom, an inherent part of supersonic flight. Before one can formulate a reasonable system of legal rules which should be applied to sonic boom damage, one must first achieve a basic understanding of what a sonic boom is, how it is produced, and how it can affect persons and property.

A. Sonic Boom Production by Supersonic Airplanes

The properties of ordinary sound are an appropriate starting point. A drop of water striking a pool of water creates a small wave that expands in a circle around the place where the drop hit the water. In a similar manner, a sharp disturbance in the air creates a wave of agitation called a source or sound wave which expands outward from the place of disturbance.[1] When such a wave reaches our ears, we perceive sound. Ordinarily the wave-generating object will cause a number of air disturbances in a short period of time. For example, a piano string, when struck sharply, will vibrate back and forth, perhaps 400 times a second; and those movements will produce an equal number of consecutive sound waves, just as drops of water from a faucet into a sink create an equal number of rings of waves (see Figures 1 and 2). The number of these sound waves produced in a given time determines the frequency of sound,

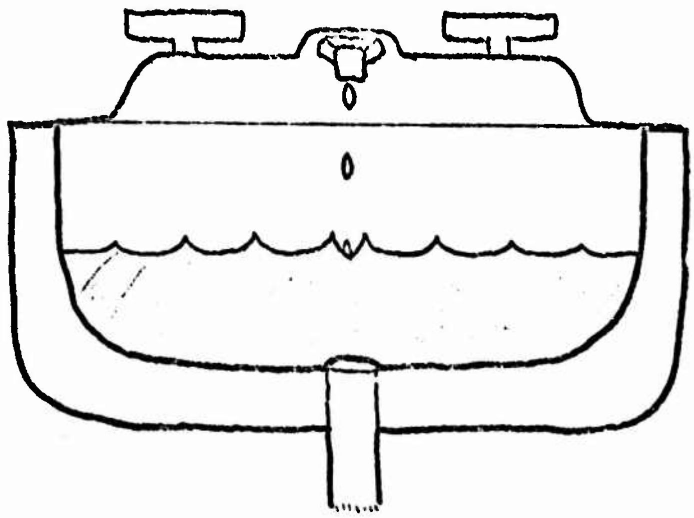


FIGURE 1. Cross section of water in a sink showing waves produced by drops striking the surface.

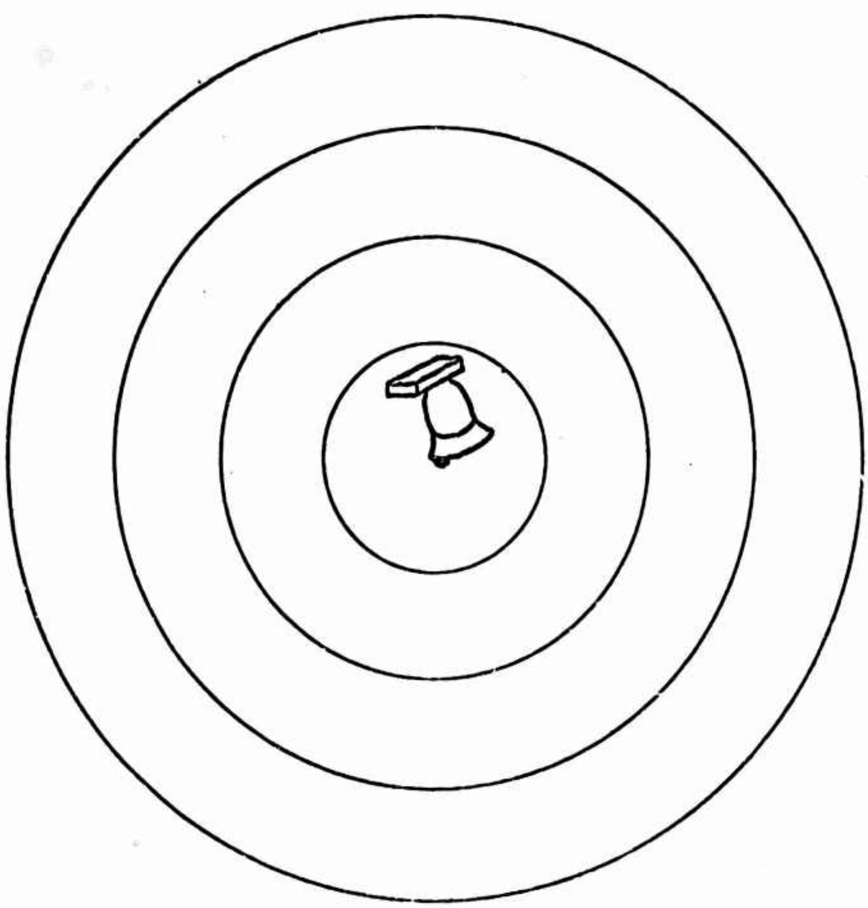


FIGURE 2. Cross section of air showing sound waves produced from disturbances caused by a stationary source. -- here a bell.

which our ears interpret as the pitch of the sound. The higher the frequency of the waves, the higher the pitch perceived by the ear.

When the source of the sound waves is stationary and the air through which they pass is uniform, the distance between consecutively produced waves depends entirely upon how rapidly the sound waves are produced. However, when the source is moving, as in the case of a subsonic jet airplane, the sound waves which have moved out ahead of the plane in the direction of flight are closer together than those that have moved opposite the direction of flight, as illustrated in Figure 3. When the source of sound waves moves faster than the speed of sound, as in the case of the supersonic transport, the sound waves expand essentially on top of one another, as shown in Figure 4.

This bunching together of sound waves forms a highly energetic front of air agitation known as a shock wave, which travels through the air like a sound wave[2] and which is closely analogous to the large bow wave produced by a boat moving rapidly through the water. This is a continuous process of disturbance that occurs throughout the period of supersonic flight, not just at the point of time when the plane "breaks the sound barrier." The shock wave can be thought of as a moving wall of compressed air. Any object the wall encounters will experience a sharp rise in air pressure -- an increase relative to the pressure of the air in front of the wave to which the object was previously exposed. A typical example of such a pressure rise is shown in Figure 5. The difference between the highest pressure experienced and the preceding pressure is called the "over-pressure," a term often used as a measure of the strength of the shock wave, just as the height of a water wave is used to describe its magnitude.

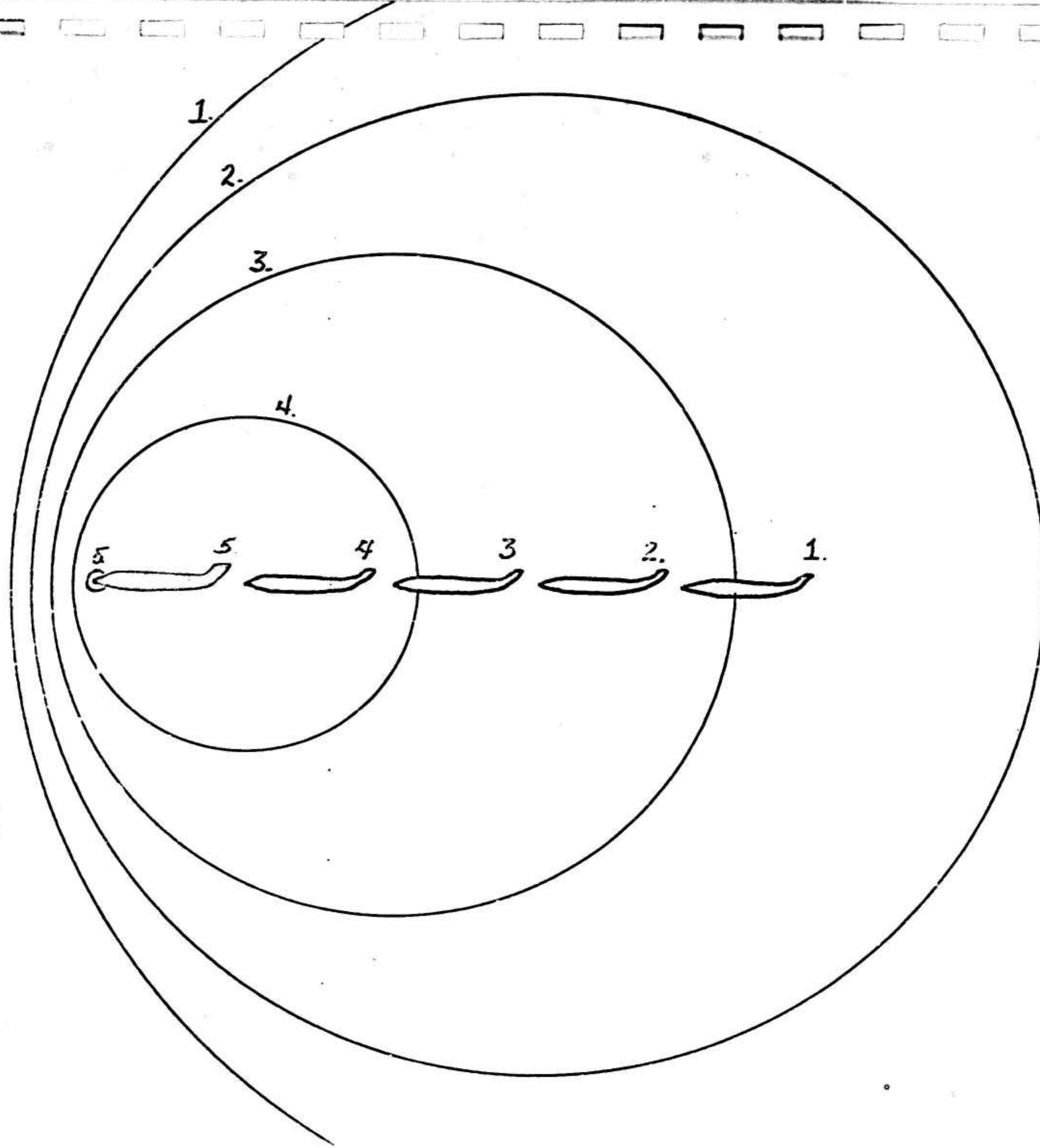


FIGURE 3. Sound wave configuration resulting from a moving source (subsonic jet moving at Mach 0.87)

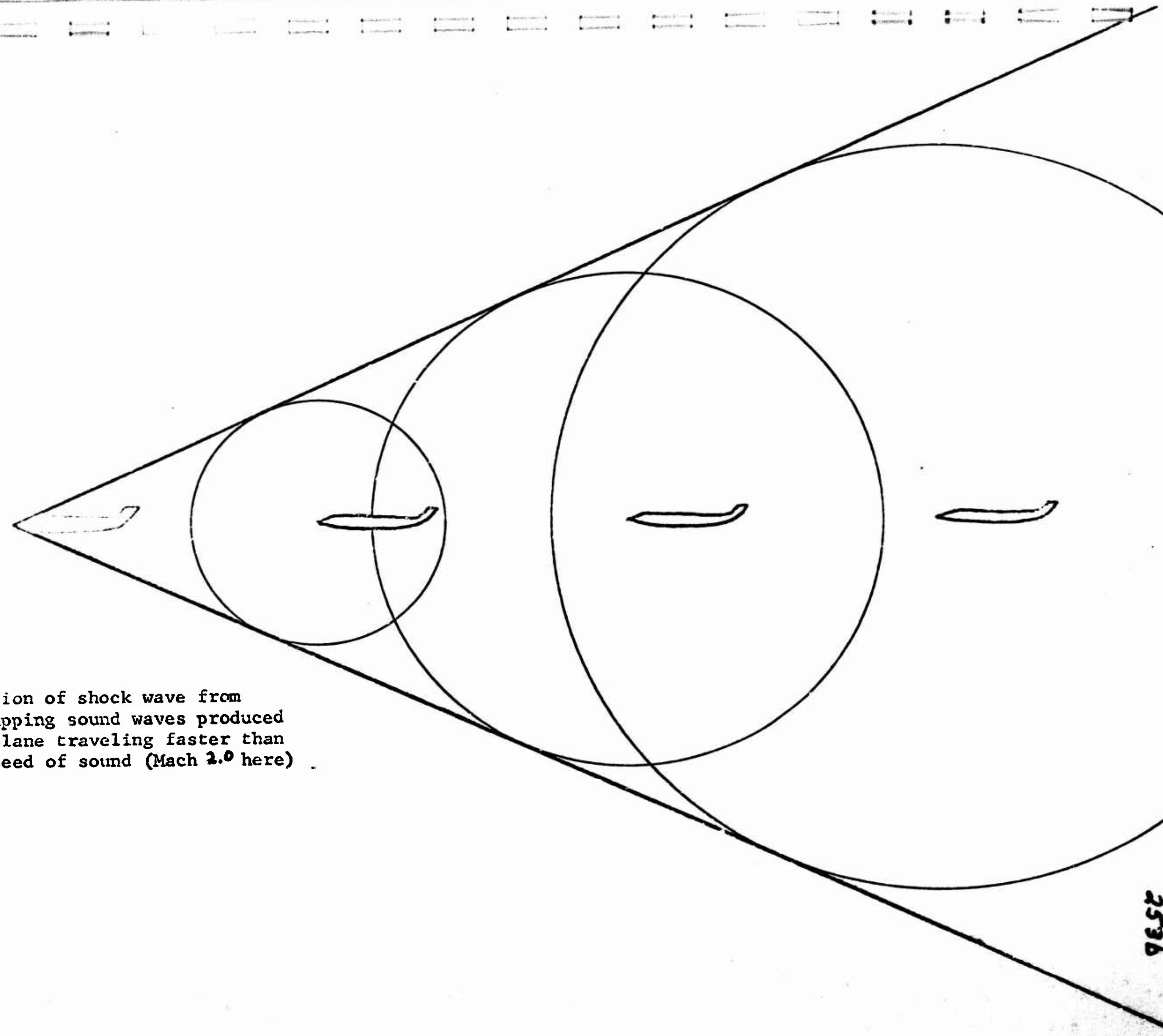


FIGURE 4. Formation of shock wave from overlapping sound waves produced by a plane traveling faster than the speed of sound (Mach 2.0 here).

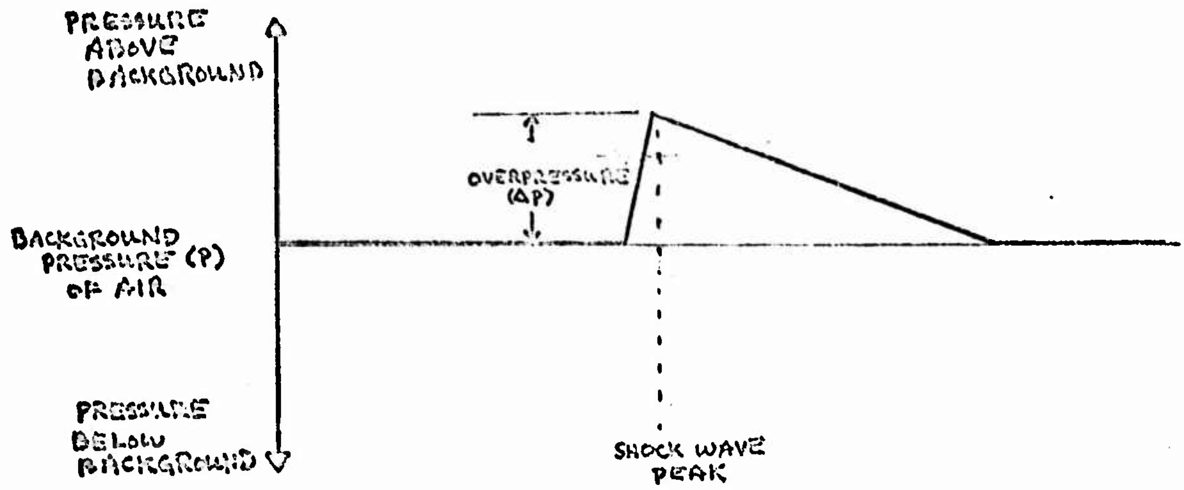


FIGURE 5. Graph showing the pressure rise accompanying a shock wave. (Often called the "signature" of the shock wave).

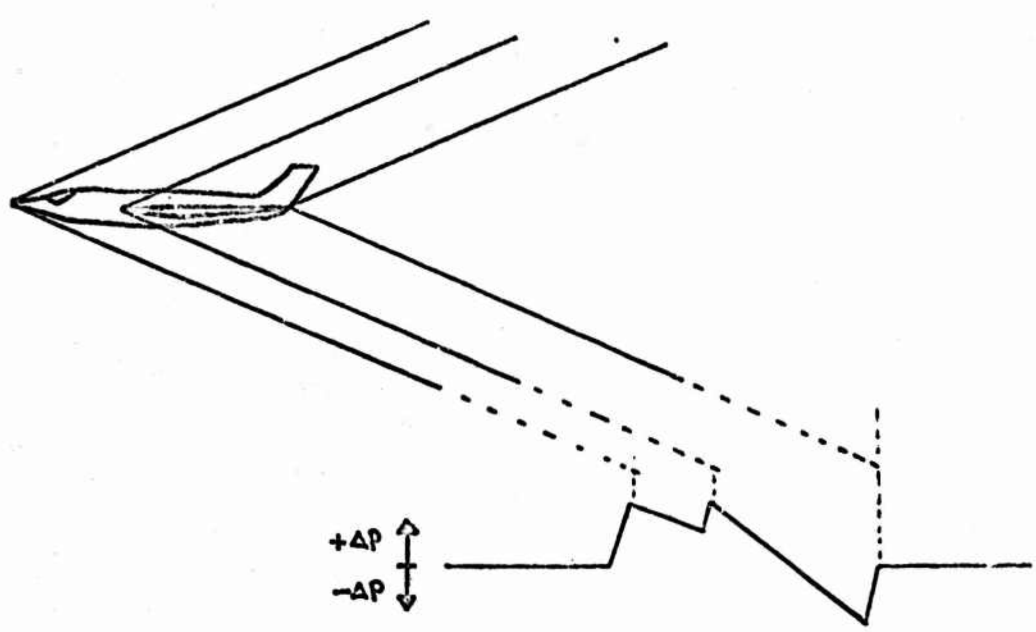


FIGURE 6. Typical supersonic transport showing production of shock waves at different parts of the plane's surface. Pressure signature near the plane is shown by graph at bottom.

As it passes through the air, a shock wave gradually loses its energy because of air friction; and, if it travels far enough through the air, the overpressure declines until the shock wave dissipates. But since the shock wave from a supersonic transport is initially quite strong, and since air friction is relatively slight, such a shock wave may travel well over 50 miles in the air before dissipation.[3] Therefore, the shock wave from a supersonic transport is likely to strike persons or objects on the ground, creating the sensation of a loud bang. This sensation has given rise to the common term "sonic-boom" to designate the shock wave generated by supersonic flight--a very proper designation, since the boom we associate with an explosion is also our perception of a shock wave which the explosion produces.[4]

The initial strength of a shock wave produced by a supersonic transport depends not only upon the size, shape, and weight of the airplane,[5] but also upon the speed and altitude of flight. Generally speaking, the bigger, heavier, and faster the airplane, the stronger the initial shock wave.[6] On the other hand, the initial shock wave is less strong if generated at high than low altitudes, because at higher altitudes the air is "thinner" and there are fewer air molecules for the plane to push ahead of itself.[7]

Applying these generalizations to the proposed American supersonic transport, we can see immediately that the initial shock wave will have considerable energy. In contrast to the Air Force B-58 bomber, one of the largest supersonic aircraft presently employed, which has a length of 100 feet, a weight of 50 tons, and a maximum speed of about Mach 2,[10] the SST is expected to be nearly 300 feet long (the length of a football field) and will weigh about 300 tons;[8] even though its cruising altitude

will be in the rarified air between 60,000 and 70,000 feet, (12-14 miles), the SST's high speed of Mach 2.7 (1800 MPH)[9] will ensure extensive collision with air molecules and strong resultant shock waves. Indeed, one of the technical problems faced by designers of the aircraft is the great heat produced on the surface of the plane by the friction created by its collision with air molecules at 70,000 feet.

Shock waves are produced by a supersonic aircraft at each place where the surface of the plane greatly disturbs the air during flight. For example, the simple airplane configuration shown in Figure 6 produces major shock waves at the front of the plane, the leading edge of the wing, and the back edge of the wing and tail. In that same figure, the rise in pressure near the airplane that corresponds to each shock wave may also be seen. As these shock waves move through the air, the ones produced between the front and tail waves tend to approach those two waves and eventually coalesce with them as shown in Figure 7.[11] Figure 8 shows clearly that the maximum overpressure of the shock waves is greater after than before combination.[12] For the supersonic transport cruising at 60,000 to 70,000 feet, this combination will occur before the shock waves hit the ground. However, it is believed that at altitudes of 40,000 feet or less this combination will not occur before the shock waves strike the ground; so the exact size and shape of the plane may have an important effect on the overpressures experienced on the ground from shock waves produced at these lower altitudes.[13] Unfortunately, the airplane shape which produces the least strong set of shock waves before combination is not the same shape which gives maximum flight and maneuvering efficiency, so the minimum sonic boom configuration increases the operating cost of the airplane.[14]

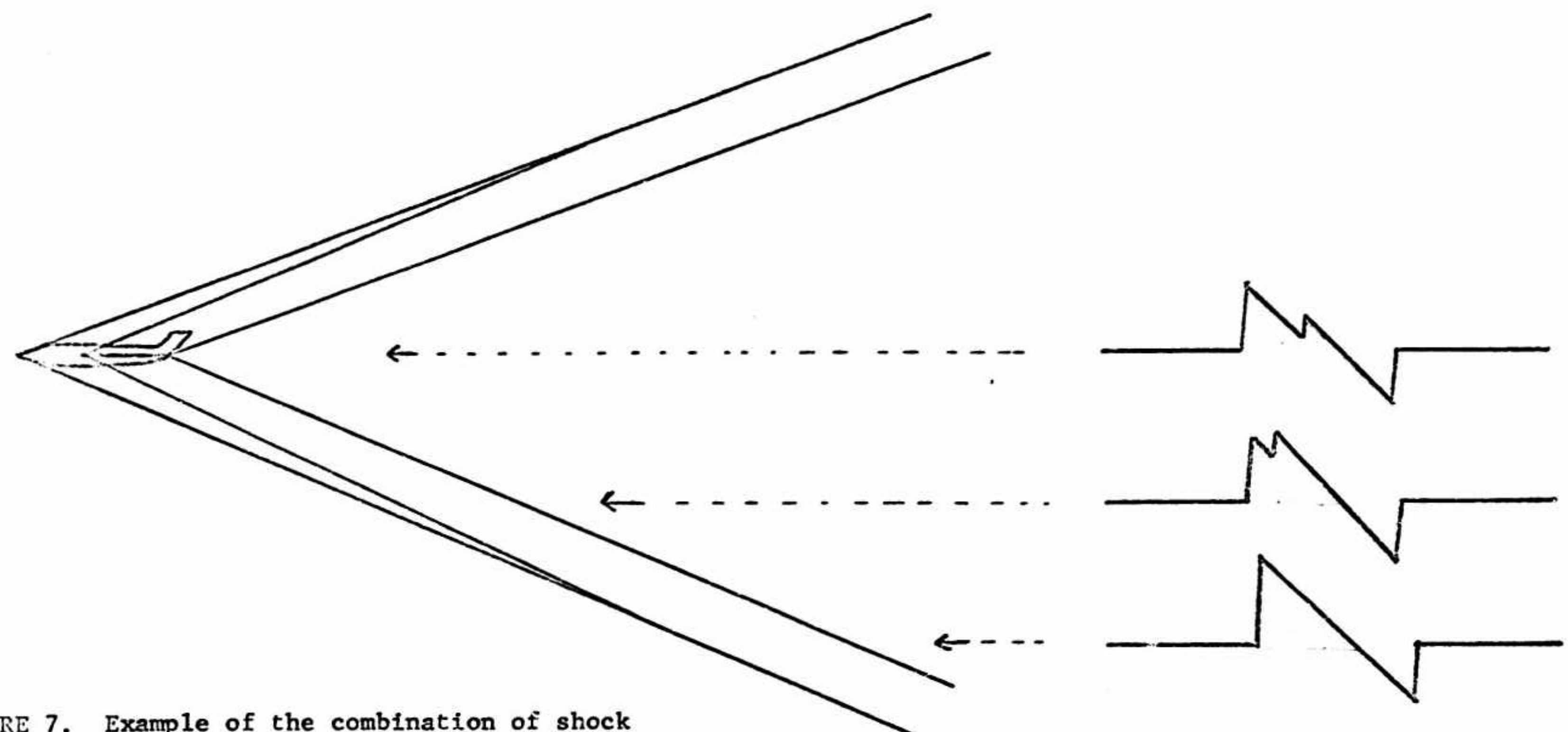


FIGURE 7. Example of the combination of shock waves produced by a supersonic transport into two main shock waves after traveling through the air for a certain distance.

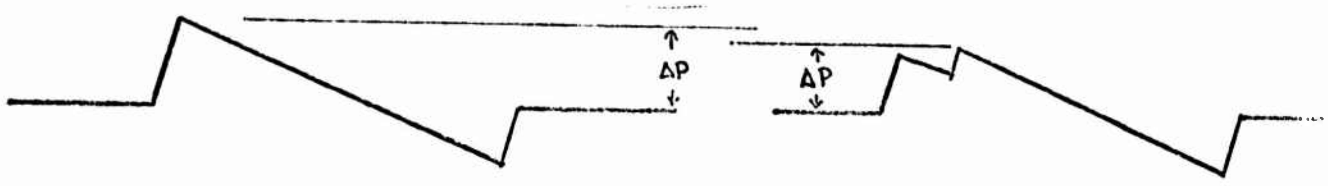


FIGURE 8. Comparison of the overpressure of shock waves produced from a supersonic transport before and after combination of the shock waves.

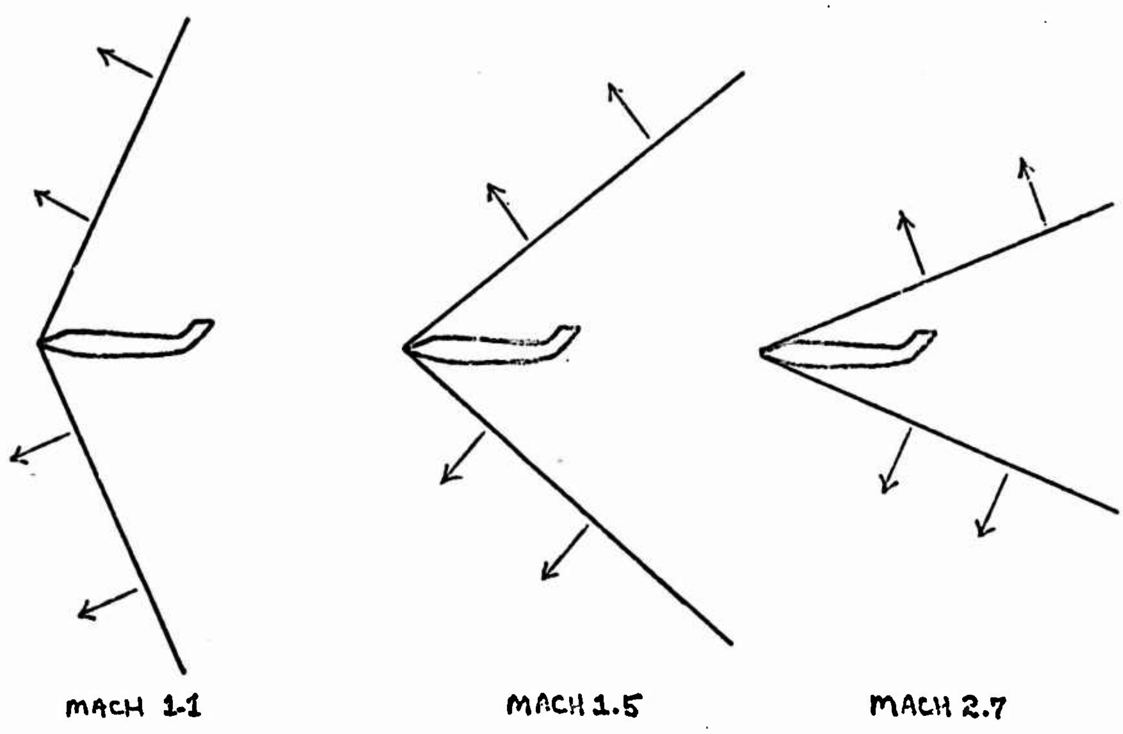


FIGURE 9. Different directions of travel of shock waves formed by aircraft moving at different speeds.

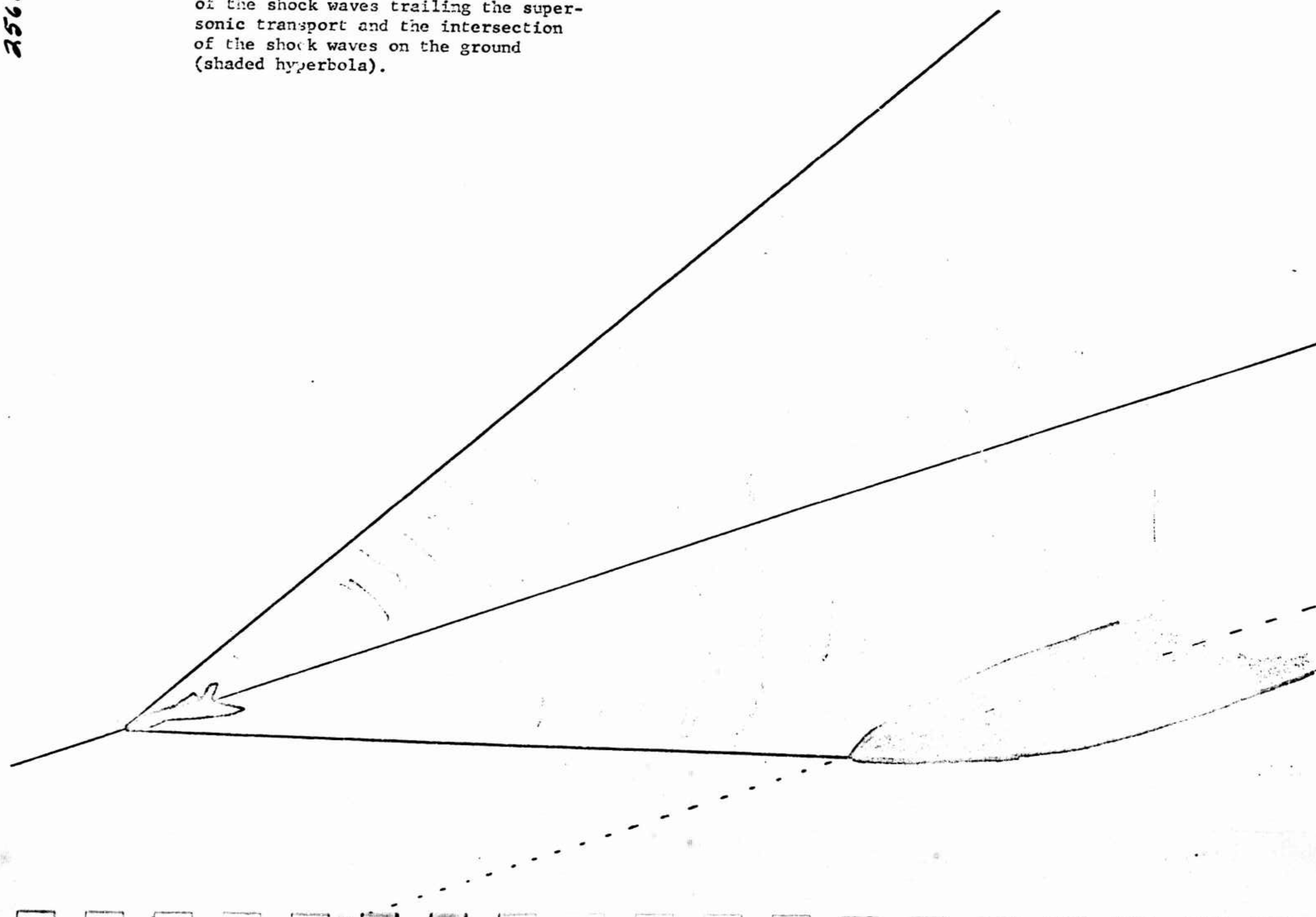
B. Variations in Sonic Boom Strength.

In order to determine the possible strength of SST generated shockwaves as they reach the ground, we must focus our attention on the front, or leading, shock wave an SST would produce. The direction in which the shock wave initially travels depends upon the speed of the plane at the time the agitation is produced. Examples of shock waves produced at different speeds are shown in Figure 9. At a given time, the whole shock wave that has been produced during the prior few seconds by the front of a plane moving at a constant speed looks like a cone trailing the plane, at least when the atmosphere is considered to be perfectly uniform.

Two characteristics of the shock wave must be carefully distinguished. The wave front sweeps back from the plane in the conical shape illustrated. But the direction of movement of any part of the wave front and of the energy in the wave front is perpendicular to the front. Analogy can be made to ocean waves breaking on a beach. One observes a line of breakers--the wave front--parallel to the shore. But the movement of the wave, and more particularly of the energy of the wave, is toward the beach. Thus, in Figure 9, the wave fronts are shown by solid lines sweeping back from the nose of the plane; and the direction of movement of each wave is shown by the arrows.

If the plane is flying level with the ground, this cone intersects the ground in the form of a hyperbola, as shown in Figure 10. We must not forget that this cone is only a picture of the shock wave at a given moment, and that each portion of the shock wave actually moves in a direction perpendicular to the wave front. A series of impacts between the wave and the ground will occur as indicated by the dotted

FIGURE 10. Diagram showing both the conical shape of the shock waves trailing the supersonic transport and the intersection of the shock waves on the ground (shaded hyperbola).



line in Figure 11. The part of the shock wave which is produced by the airplane at a given place in the air travels along a path as shown in Figure 12. Since the wave must travel farther through the air to reach the ground if it is directed out to the side of the plane than if it is directed beneath the airplane, the shock wave which reaches the ground to the side of the path of flight is less strong (ignoring atmospheric distortion for the moment) than that which reaches the ground directly beneath the path of flight.

At a certain distance away from the path of flight, the shock wave has to travel so far before reaching the ground that it becomes dissipated in the air; thus the width of the affected area on the ground is limited by the strength of the initial shock wave.[15] Comparative strengths of shock waves reaching the ground at different distances from the path of flight are illustrated in Figure 13 for a typical supersonic flight.[16] Estimates of the width of the area which will be affected by the American supersonic transport, traveling at cruising altitude and speed, range from 30 to 80 miles. Of course the affected area extends along the entire path of supersonic flight as illustrated in Figure 14. Since supersonic speeds are expected to be attained between 100 and 200 miles from the airport of origin and to end about 100 miles from the destination airport, a typical flight such as New York to Los Angeles will affect the large swath of territory shown on the map of the United States in Figure 15.

1. Atmospheric Distortions.

The strengths of shock waves striking the ground along the path of flight will not be consistent,[17] for the single conical form of the shock wave which has been described does not adequately represent the

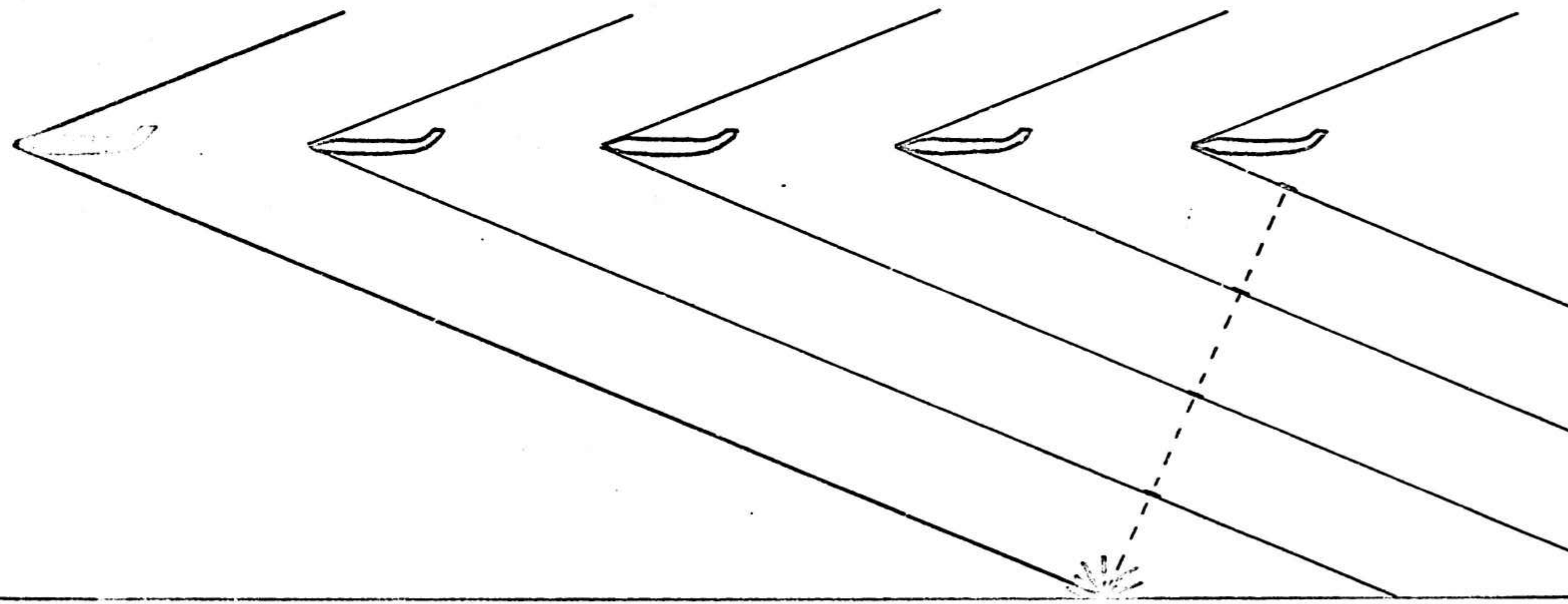


FIGURE 11. Diagram showing the actual path of travel of energy in the shock wave.

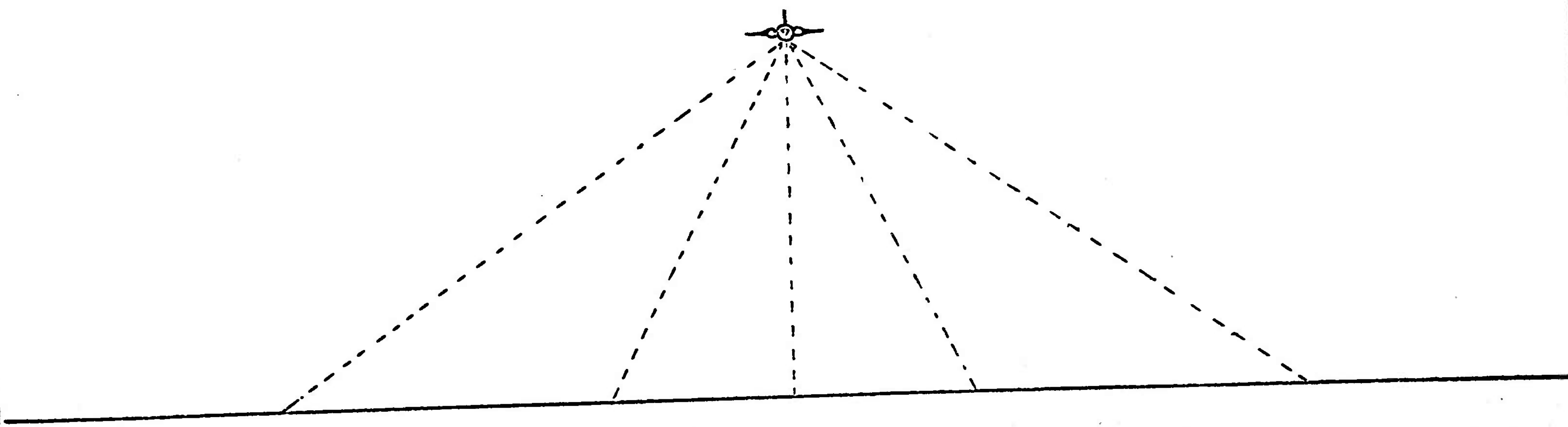


FIGURE 12. Front view of a supersonic transport showing the relative distance of travel in the air for shock waves striking the ground at different distances from the line of flight.

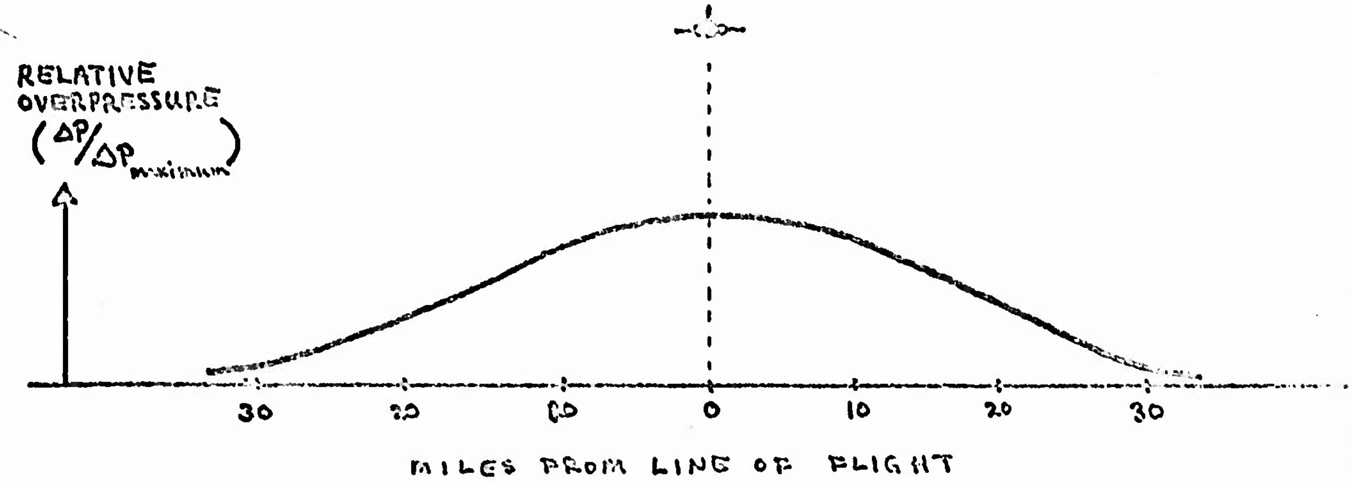


FIGURE 13. Relative overpressure of the shock wave at different points on the ground as measured from the line of flight.

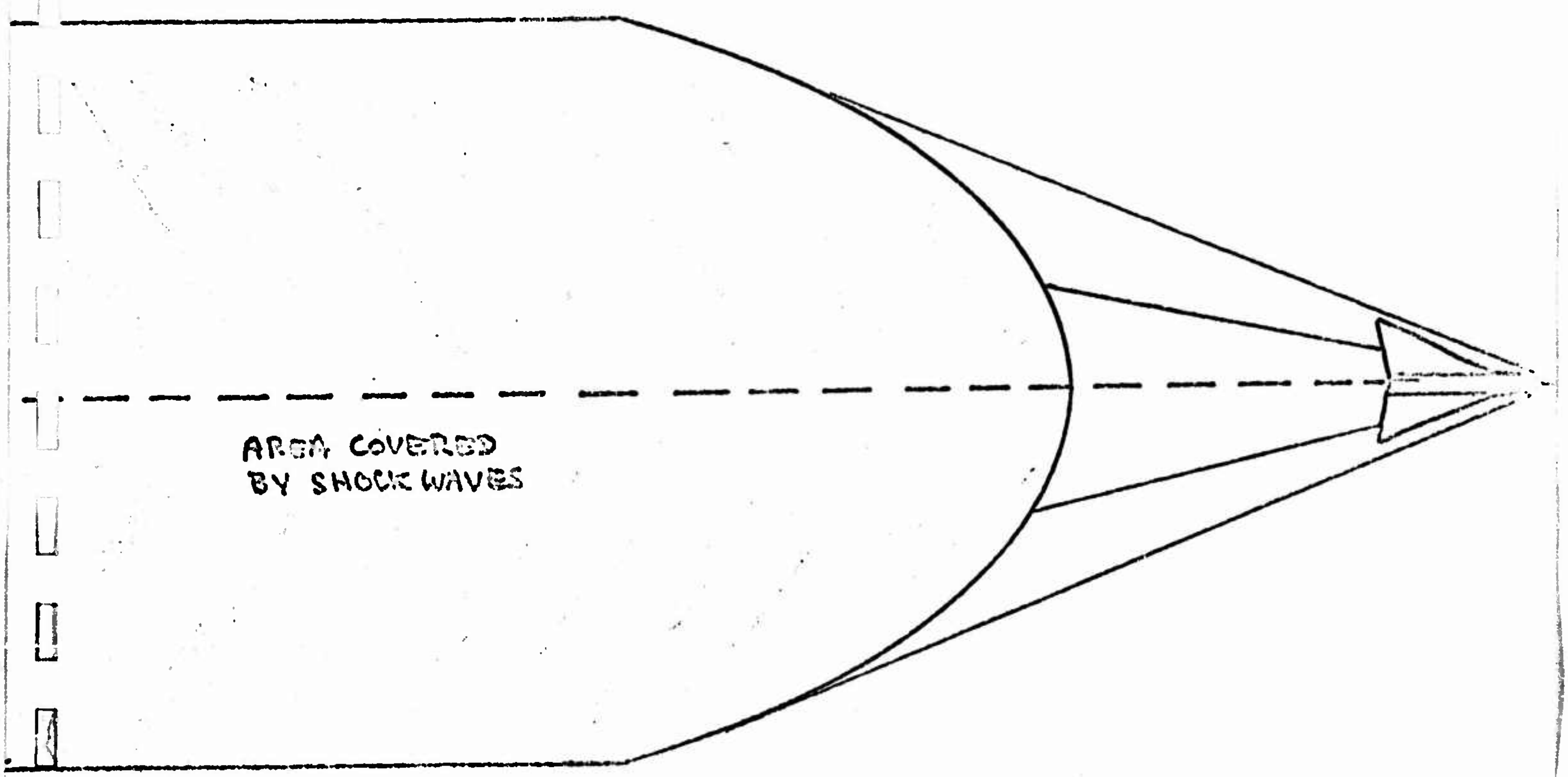


FIGURE 14. View from above the airplane showing the area covered by the shock wave (sometimes called the sonic boom "carpet").

FIGURE 15. Map of the United States showing the area affected by the shock waves produced during a single Los Angeles to New York flight.

possible variations in shock waves which will be caused by an actual plane in the actual atmosphere. We must now examine one by one the effects of certain meteorological phenomena and then combine these effects to illustrate the relative strengths of shock waves striking the ground under common atmospheric conditions.

a. Temperature Effect

The non-uniform aspect of the real atmosphere with which we are most familiar is its variable pressure. At high altitudes, the pressure is much less than at sea level. Up to 35,000 feet altitude, this pressure decrease is accompanied by a substantial decrease in the temperature of the air from an average in the United States of 50°F at sea level to -70°F at 35,000 feet.[18] The speed of a shock wave is strongly dependent upon the temperature of the air through which it passes[19] and the shock wave travels more rapidly at higher temperature. Thus the parts of the shock wave in the lower altitudes travel faster than the parts in the higher altitudes. The net result is a bending of the shock wave as shown in Figure 16. Figure 16 also illustrates a case in which the speed and level of flight are properly chosen so that the bending effect directs the lower part of the shock wave parallel to the ground, thereby preventing the shock wave from ever striking the ground. However, for the SST traveling at cruising speed, the shock wave is directed so sharply away from the line of flight, as shown in Figure 17, that this average temperature variance cannot prevent the shock wave from reaching the ground during level flight.[20]

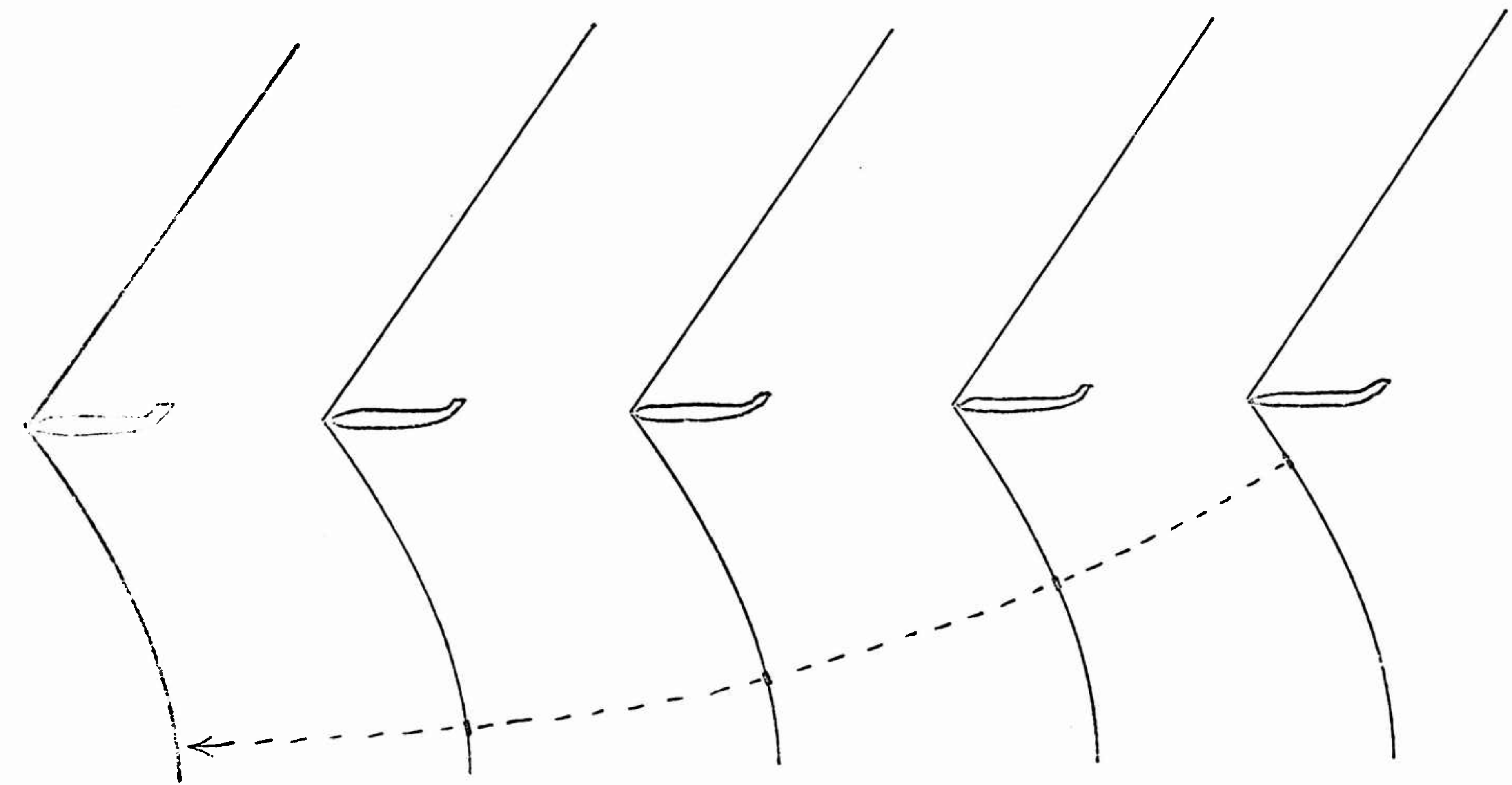


FIGURE 16. Diagram showing the effect of the atmospheric temperature gradient on the path of the shock wave. In this example (Mach 1.2 at 50,000 feet), the shock wave is deflected so it never reaches the ground.

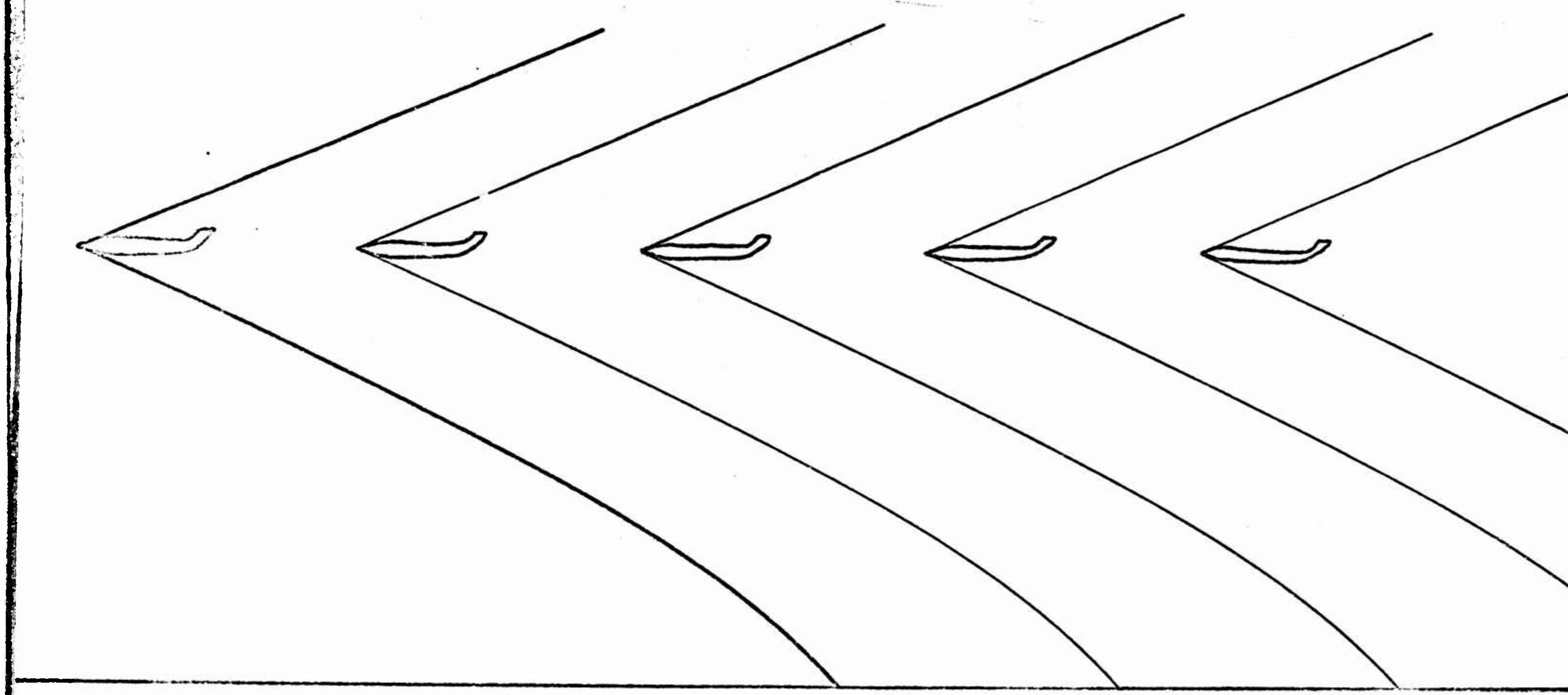


FIGURE 17. Diagram showing the effect of the atmospheric temperature gradient on the path of the shock wave produced from a supersonic transport (Mach 2.7 at 70,000 feet).

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The smooth variation of pressure and temperature which has been assumed in the preceding discussion is in accordance with a conceptual model known as the standard atmosphere, which is used as a reference for comparing different meteorological conditions.[21] The actual atmosphere rarely conforms to the model. The two localized variations from the standard atmosphere which have the greatest effect upon shock waves passing through them are temperature masses and wind regions.

Consider first the effect of a mass of air with a temperature different from that of the surrounding standard atmosphere. As illustrated in Figure 18, passage of a shock wave through such an air mass distorts the shock wave; as a result, energy initially distributed over a long segment of the shock wave tends to focus in two small portions of the wave. Consequently the strength of the shock wave at these two points is increased over its usual strength. Further passage through the standard atmosphere tends to defocus the strengthened portion and recreate a shock wave with uniform strength. Therefore, only abnormal temperature regions lying at less than 10,000 feet altitude have any detectible effect on the relative strength of the shock wave as it reaches the ground.[22]

But temperature pockets near the ground are very common--a cool pocket over a large body of water and a warm pocket over a city are typical examples. A typical focus from a warm pocket on the ground is shown in Figure 19. The exact magnitude of the focused strength of the shock wave is not clear, but a doubling of strength has commonly been predicted.[23]

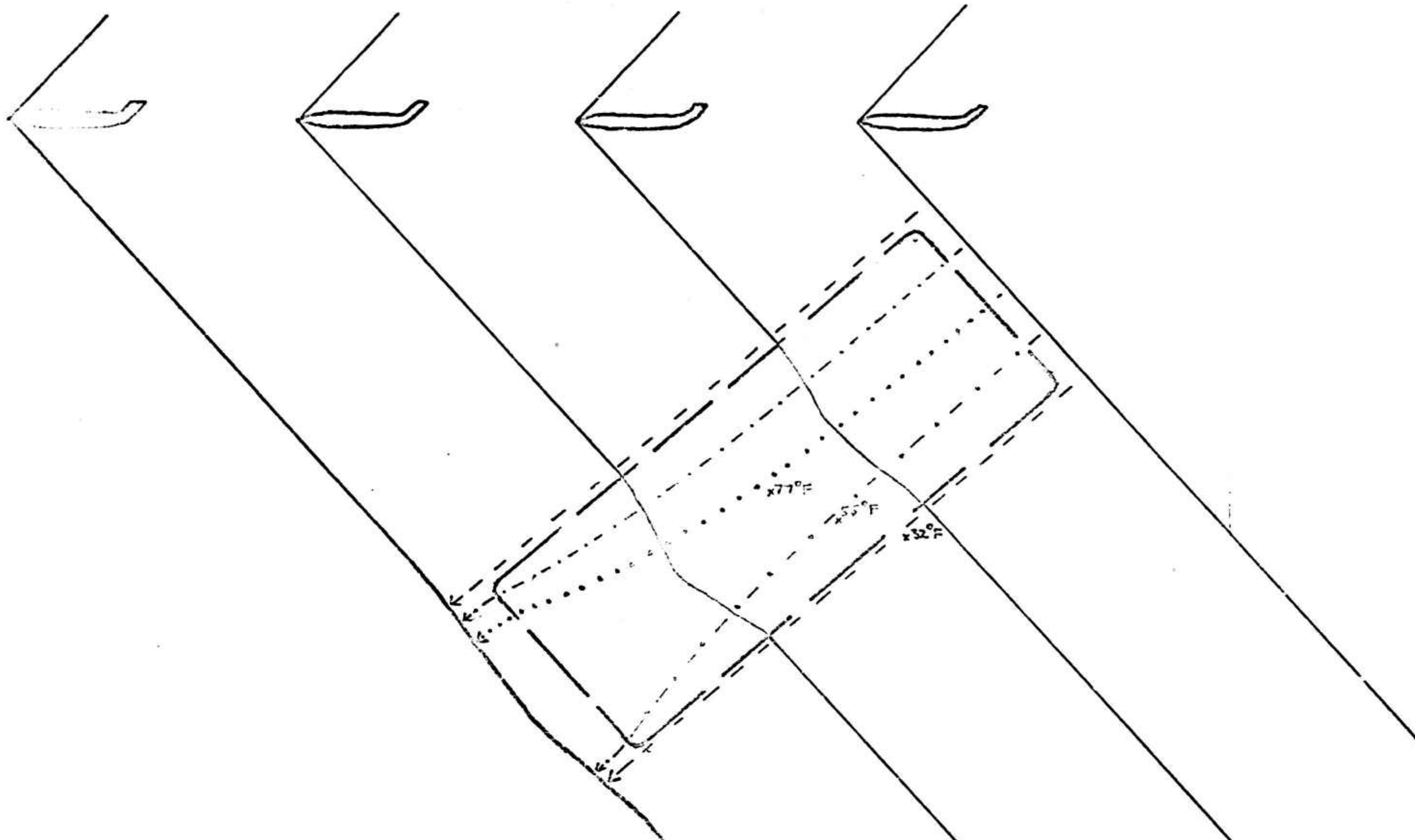

FIGURE 18. Diagram showing the effect of a temperature mass on the configuration of a shock wave passing through it. (Curvature slightly accentuated for illustration purposes).

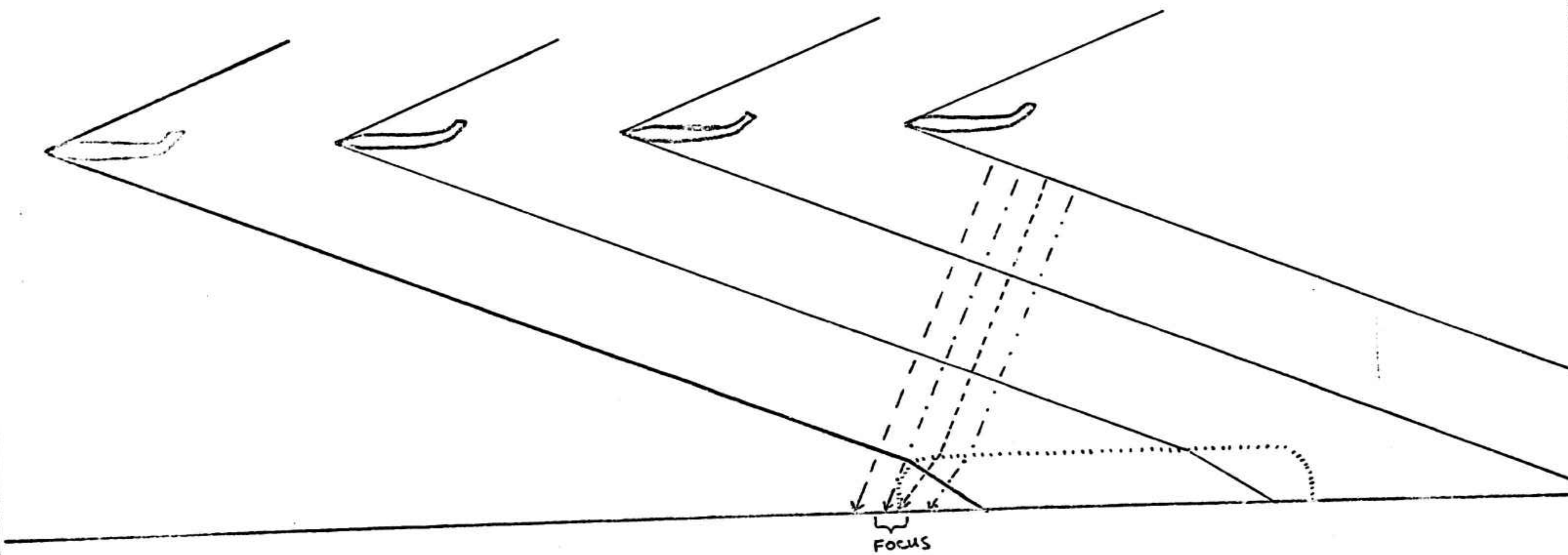

FIGURE 19. Diagram showing the focusing of the shock wave caused by a warm air mass resting on the ground (and extending to 5,000 feet).

In addition to this focus effect, a recent study has shown that passage of the shock wave through air colder than the standard atmosphere involves less dissipation of energy than passage through warmer air.[24] This means that during the winter identical initial shock waves will strike the ground with more energy than in the summer.

b. Wind Effect

In addition to the temperature masses, regions of winds are potential causes of increased strength of shock waves passing through them. Wind, quite simply, is the movement of the very medium through which the shock wave passes. The direction of the wind is crucial in determining the distortion of the shock wave, just as the direction of water flow in a stream is crucial in determining where a swimmer crossing the stream will land on the other side. A very simplified sketch of the effect of a wind region on a shock wave is shown in Figure 20.

Increases in the relative strength of the shock wave created by wind regions are nullified by further passage of the shock wave through the windless standard atmosphere. One study has indicated that wind magnifications created above 15,000 feet altitude cannot be detected in the shock wave by the time it reaches the ground. If it is correct, this proposition indicates that jet streams (centered around 35,000 feet) are not significant sources of shock wave magnification.[25] However, winds commonly extend to ground level, and very strong unpredictable winds may be expected below 15,000 feet.

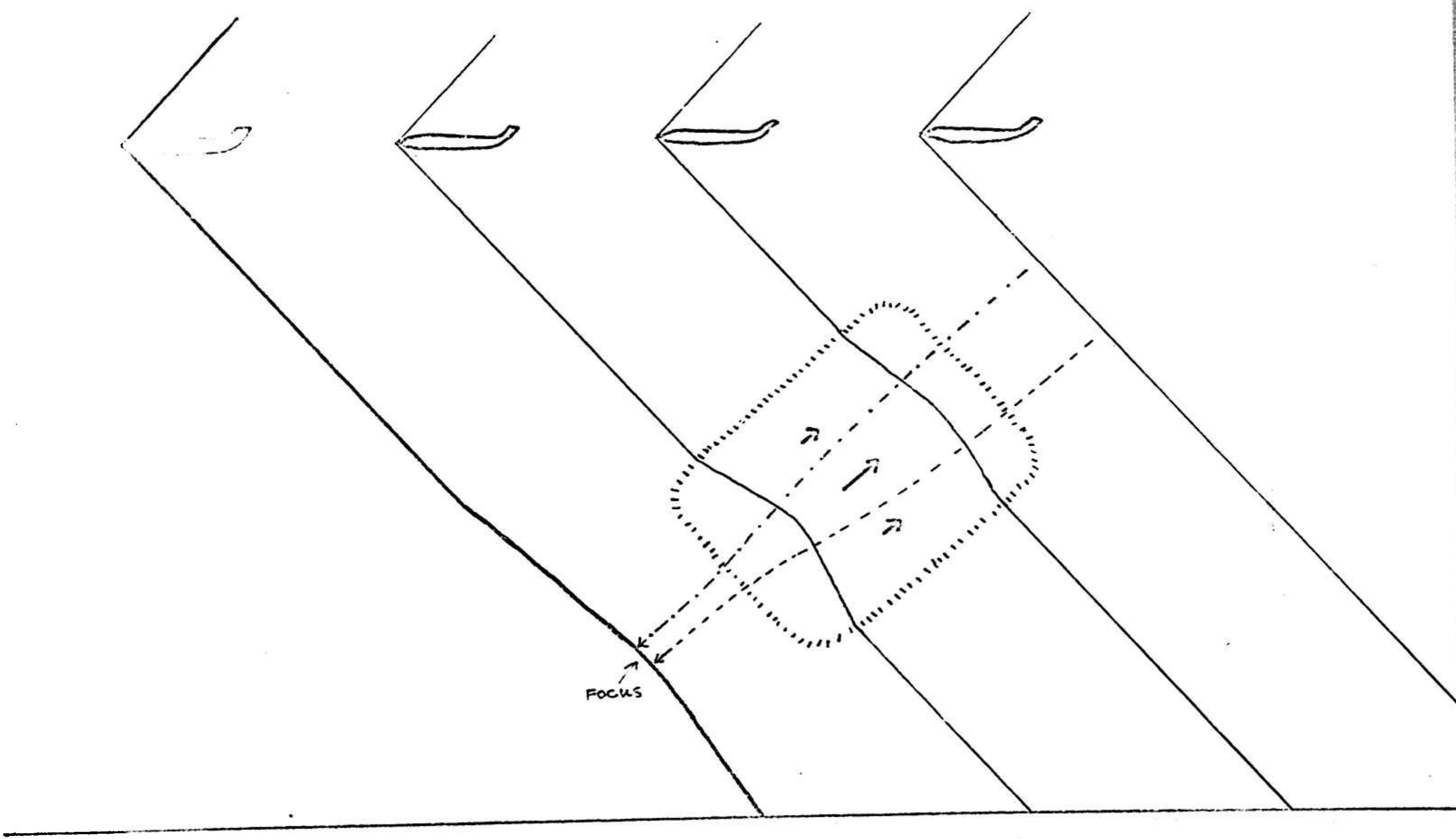

FIGURE 20. Diagram showing the effect of a wind region on the configuration of a shock wave passing through it. (Curvature slightly accentuated for illustration purposes)

The wind effect on a shock wave has not been thoroughly investigated, and the extent of possible magnification does not seem to be agreed upon. The two most detailed studies indicate that two-fold magnification of the normal shock wave strength may occur, but neither study attempts to determine the magnification resulting from very localized winds which would be expected to focus the shock wave sharply into a particular place.[26] Of course, not all the effects are adverse: some winds may actually prevent parts of the shock wave from reaching the earth.[27] But wind effects will cause marked variations in both the strength and direction of movement of the shock wave.

Because atmospheric variations of temperature masses and wind regions will often occur at the same time and place, the effects of the two phenomena on a shock wave will often occur simultaneously with the result that a single shock wave may very commonly have double strength and sometimes triple strength merely because of ordinary variations in the atmosphere through which the shock wave must travel. Even the relatively scanty results from experiments which have been conducted up to the present time have shown these magnification effects.[28] For example, Figure 20a which is derived from the Chicago tests in 1965 shows that double magnifications occur about 0.5 per cent of the time. Lundberg's analysis of the Oklahoma City tests indicate similar probabilities although his results are probably extrapolated from the actual experimental data.[29] Figure 20b shows these results and also shows the actual area which would be affected by the magnified shock waves during a single supersonic flight from Los Angeles to New York.

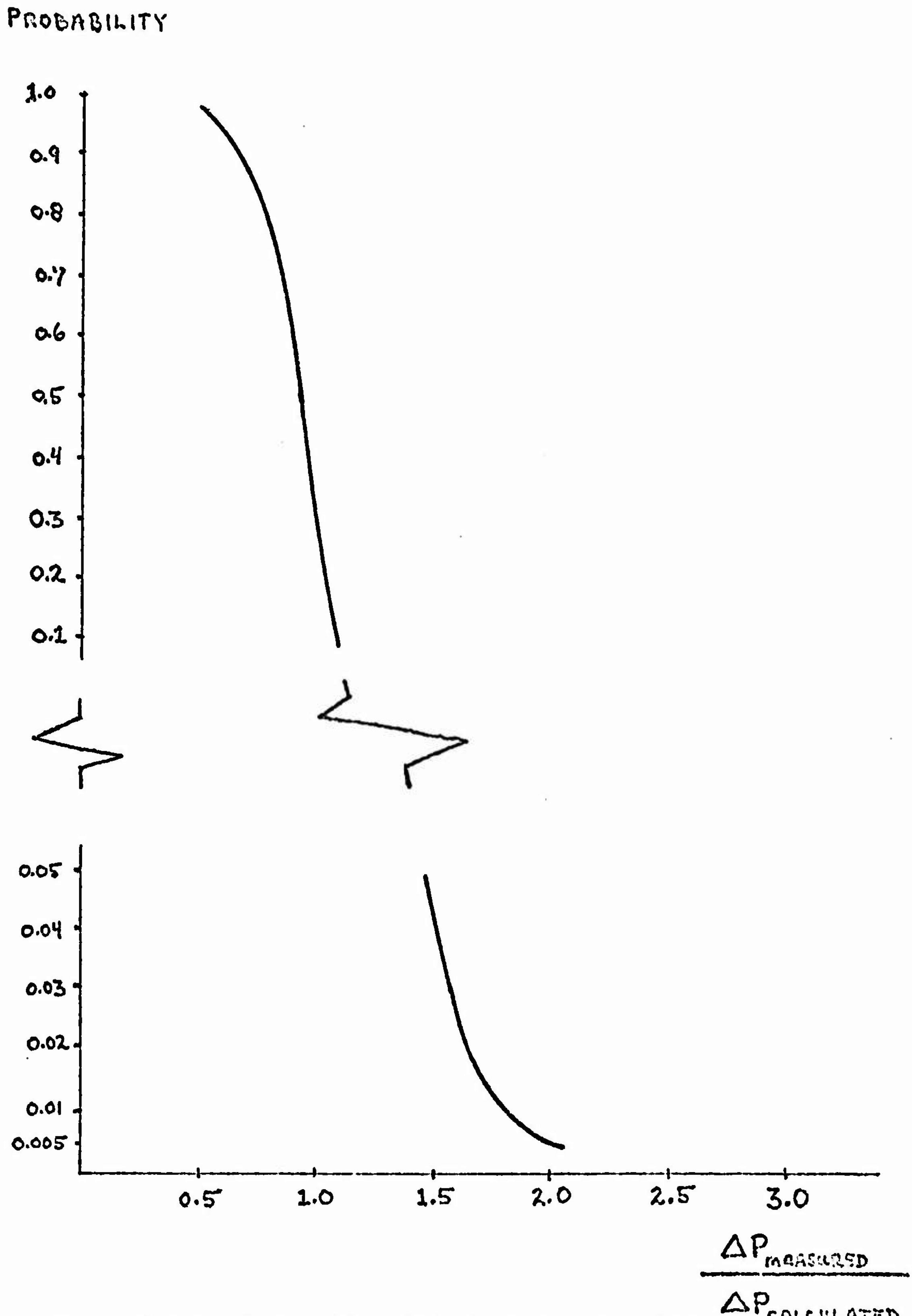

FIGURE 20a. Graph of experimental data showing the probability of shock wave amplification. The scale used along the probability axis is different on the bottom half of the curve than on the top half to show the curve more clearly at the lower probability levels. (Based on the Chicago tests cited in footnote 27a).

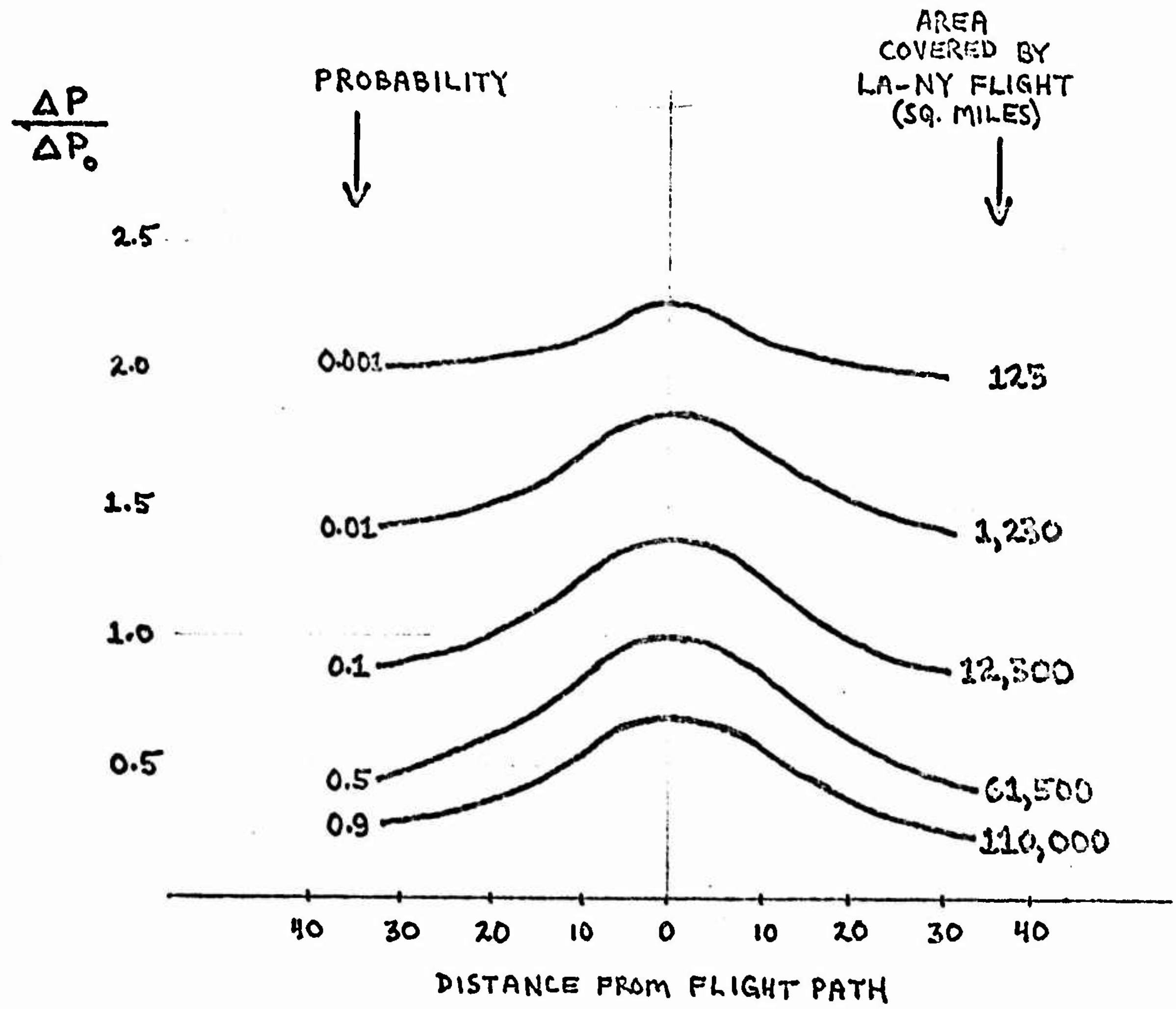

FIGURE 20b. Graph showing the probabilities that a given shock wave of normal pressure x will be stronger or weaker than x at various distances from the flight path.

For example, the graph illustrates that a wave at least twice as strong as x will occur with a probability of .001 (.1% of the time) at a distance 33 miles from the flight path. It is equally probable (.001) that the wave will be at least 2.25 times as strong as x on the flight path. A wave at least as strong as normal strength x (multiple 1.0) is shown to occur along the flight path with a probability of 0.5.

The numbers in the left hand column indicate multiples of normal wave strength (x) from .5, or ½, to 2.5, or 2½. The numbers at the left end of each curve indicate the probability value of the curve; that is, the probability that multiples of shock wave strength, at least as strong as those indicated by the numbers in the left hand column, will occur at any given distance from the flight path.

The figures in the right hand column show the number of square miles of land that would be exposed to overpressures having the probability value of the curve to the number's left on a single Los Angeles-New York flight. Thus it is indicated that 1,230 square miles will be exposed to overpressures at least 1.4 to 1.8 times normal strength during such a flight.

From that figure, it is apparent that these seemingly infrequent magnifications will affect very large areas; indeed, over the course of a year's flights, very few parts of the areas traversed by SST's will remain untouched by a magnified shock wave.

2. Maneuvers

The causes of shock wave distortion so far examined are those which can affect the strength of a wave produced by an SST flying straight, level and at constant speed. Additional complications and magnifications may be introduced by aircraft maneuvers which the SST will be required to make.

At least once each flight, the SST will accelerate from subsonic to supersonic speeds. This acceleration through speeds in the Mach 1 range will cause focusing and concentration of the shock waves being generated during that acceleration. Since the causes of wave focusing are similar in the case of most maneuvers it is appropriate to examine the acceleration phenomenon in some detail; thorough understanding of this instance of focusing will facilitate consideration of other maneuvers.

Recall that the shock wave front is almost perpendicular to the flight path at Mach 1 and forms an increasingly sharp angle with the flight path as speed increases; and recall that the direction of energy transmission is perpendicular to the wave front. As the SST accelerates through different speeds, no two of the wave fronts caused will be precisely parallel to one another, and hence no two energy paths will be parallel. As illustrated in Figure 21, the energy released at Time 1 is "aimed" at a point on the ground well forward of the plane's position at that time. At Time 2 the plane has advanced, and energy released at Time 2 is aimed more nearly straight down at about the same point on

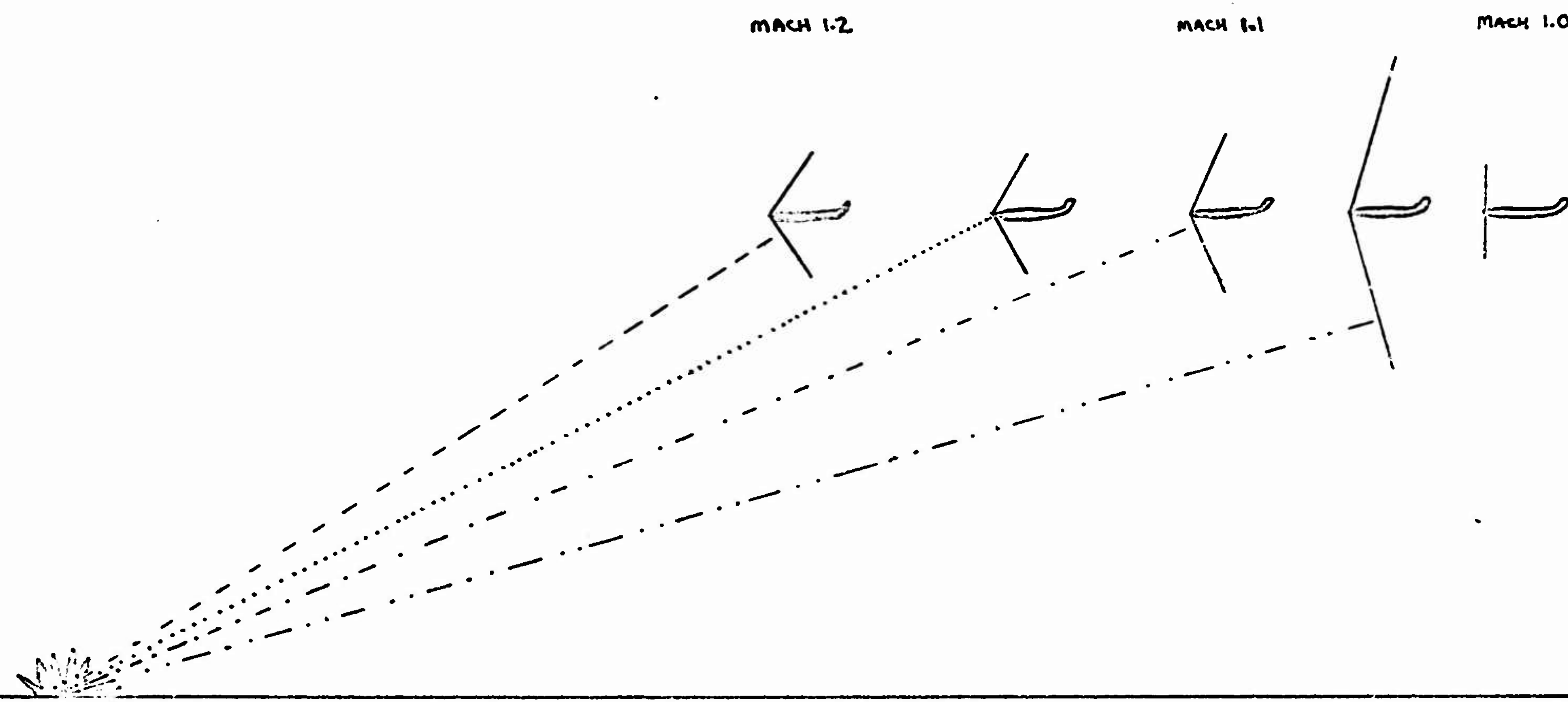

FIGURE 21. Diagram showing the focus caused during acceleration from subsonic to supersonic flight by the changing propagation directions of the shock wave. For illustration purposes, only the parts of the shock wave near the propagation point are shown.

the ground at which the first shock was aimed. Moreover shock number two has a shorter distance to travel so that it tends to catch up with and reinforce shock number one. For this reason there is a significant focusing of energy at that area on the ground where the "sonic boom carpet" first occurs. An area in the shape of a horseshoe (with the open end of the horseshoe in the direction of flight) will experience overpressures of unusual intensity.

An analogy may assist full understanding of the acceleration, or horseshoe, phenomenon. Imagine that a firetruck is being driven down the street by a playful fireman who decides to squirt a friend with the fire hose. He aims the hose at the friend and turns on the water while the friend is well up the street, almost ahead of the truck on the sidewalk. As the truck moves closer and finally passes the friend, the fireman continues to aim, pointing the hose more and more to the side of the truck as the truck draws alongside the friend. Suppose that the speed of the truck, the velocity of the water and the distance to the friend all happened to be such that all the water particles that had been shot out on their independent journeys toward the friend over a period of many seconds, each on a diffe nt course and with a different distance to travel to the friend, happened to arrive at the same instant of time. The friend would not be wetted gently over a period of many seconds but would be struck violently by a wall of water.

A similar aggregation of shock waves striking a point on the earth is what causes the horseshoe effect. While no conscious aiming is involved, the plane sends out complete conical wall of shock waves at each moment and the directior movement of each successive wall is progressively more downward and less in the direction of flight. There

will be some particular area on the earth beneath the plane so situated as to be subjected to the focusing effects illustrated in Figure 21. The area on the ground that will be affected by this focusing can be predicted fairly closely (± 5 miles), if the atmospheric conditions are not too severe and the altitude and acceleration are known. The region that the focused pressure wave strikes looks like a horseshoe 300 feet wide below the plane's line of flight, with its open end in the direction of the plane's movement. The horseshoe encompasses an area of about one square mile.[30] This focus is generally considered to give at least a two-fold magnification of the normal shock wave strength expected from level flight at comparable speeds.

It may be possible to minimize the horseshoe focus problem by having the plane climb as it accelerates through the transsonic speed range. If the angle of climb is sufficiently great, the initial direction of shock energy and the bending of the shock waves by the temperature gradient in the atmosphere may reduce the effect by forcing the shock wave to travel a long distance through the air before striking the ground, as shown in Figure 22.

A second common maneuver by the supersonic transport is the "pushover," which is the change from a climb to horizontal flight. This maneuver also creates a strengthened shock wave on the ground since the shock waves produced during the climb meet the ground at the same time as the waves produced moments later during horizontal flight. Figure 23 shows how this reinforcement can occur by outlining the paths of several portions of the overall shock wave and by showing momentary configurations which result from the pushover maneuver.

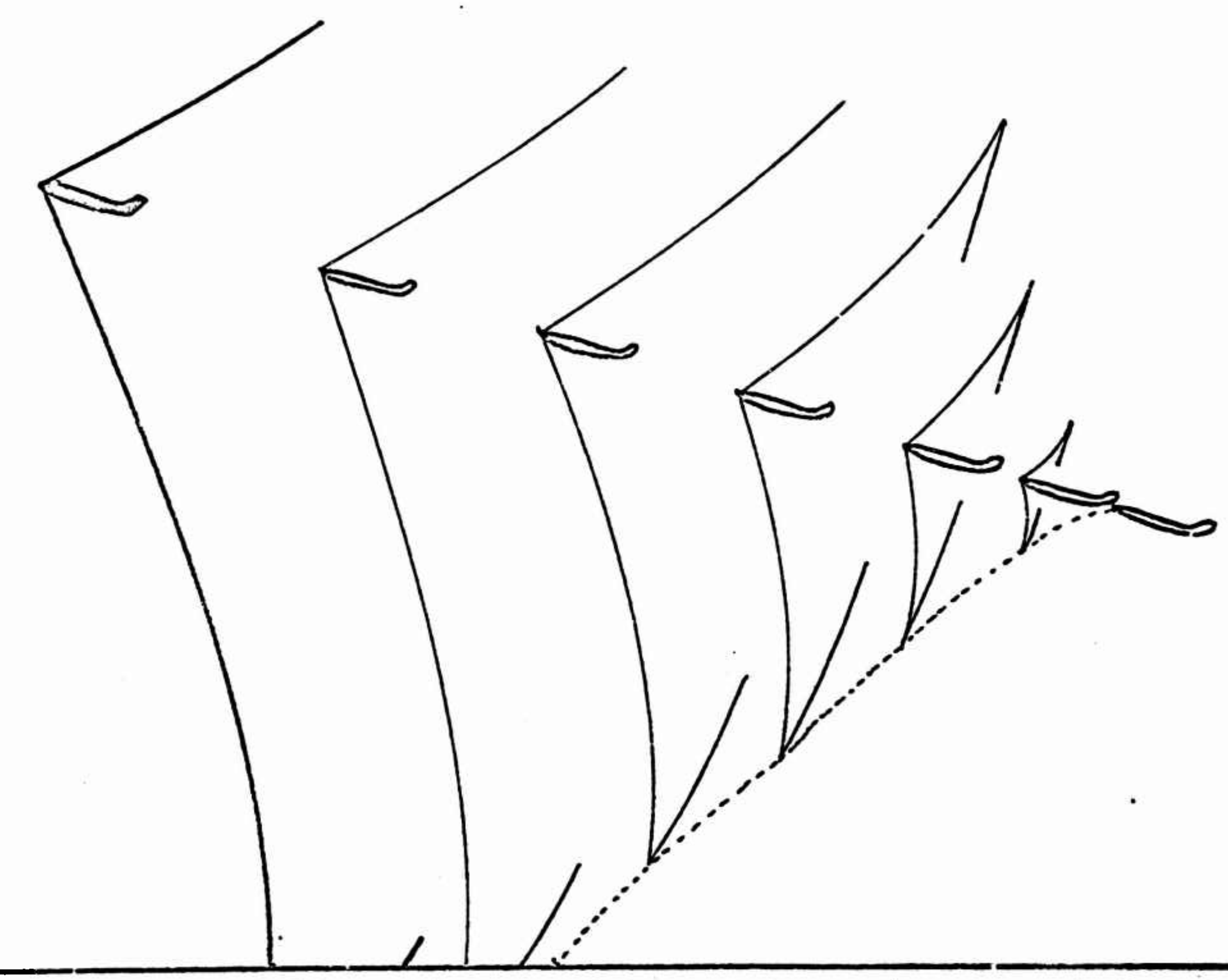

FIGURE 22. Diagram showing the effect of a climbing angle and the atmospheric temperature gradient on the magnified shock wave caused by acceleration from subsonic to supersonic speeds.

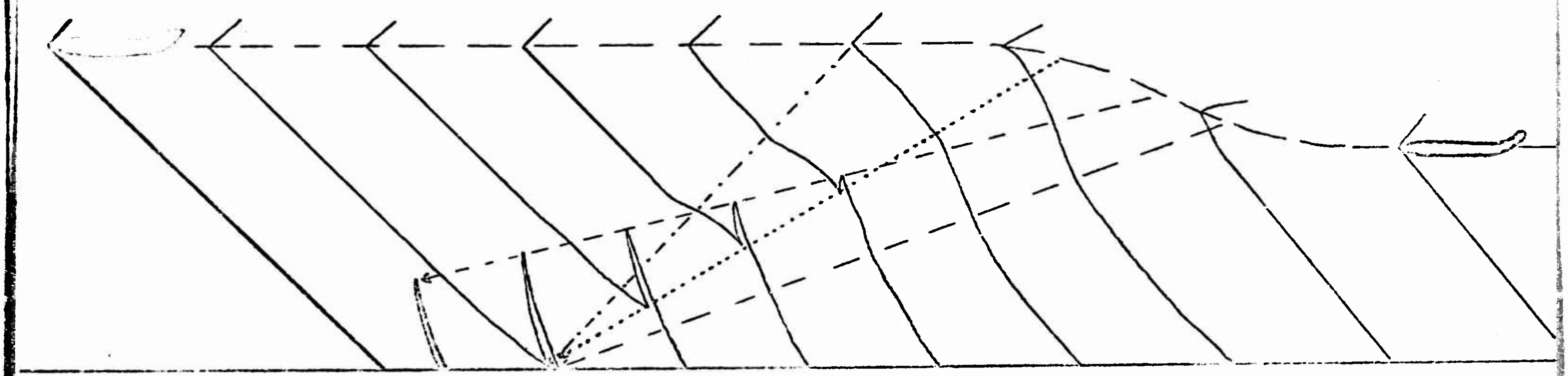

FIGURE 23. Diagram showing the reinforcement of the shock wave caused by a "pushover" maneuver in ascent.

Where the two shock waves appear to follow each other very closely, it is believed that they coalesce to form a single strengthened shock wave.

Measured shock waves having overpressures four times as great as normal have been attributed to pushover maneuvers;[31] although if the supersonic transport makes a very gradual pushover, fourfold magnifications are unlikely. A similar though less marked effect occurs when the supersonic transport leaves level flight to descend and decelerate as shown in Figure 24.

The third maneuver which may give a focusing effect upon the ground is a simple turn. The reasons for this focus are the same as for the pushover maneuver, but in this case the doubling over of the shock wave, as shown by the momentary intersections of the shock wave with the ground in Figure 25, occurs only by portions of the wave which are already reduced in strength by their long travel through the air. This is to be contrasted to the reinforcement of the pushover which involves parts of the shock wave having the least distance to travel to the ground. Moreover the SST traveling at Mach 2.7 will move in almost a straight line. The only sharp turn required will be for landing, and that will be at subsonic speed. Therefore, serious magnifications of shock wave strengths caused by turning the SST probably will not constitute a major problem.[32]

A fourth problem related to airplane maneuvers is the simultaneous ground intersection of two shock waves produced from two different supersonic transports passing near one another (30 miles is sufficiently close). Figure 26 shows clearly that the two shock waves generated by two passing supersonic airplanes will reach some place on the ground at the same

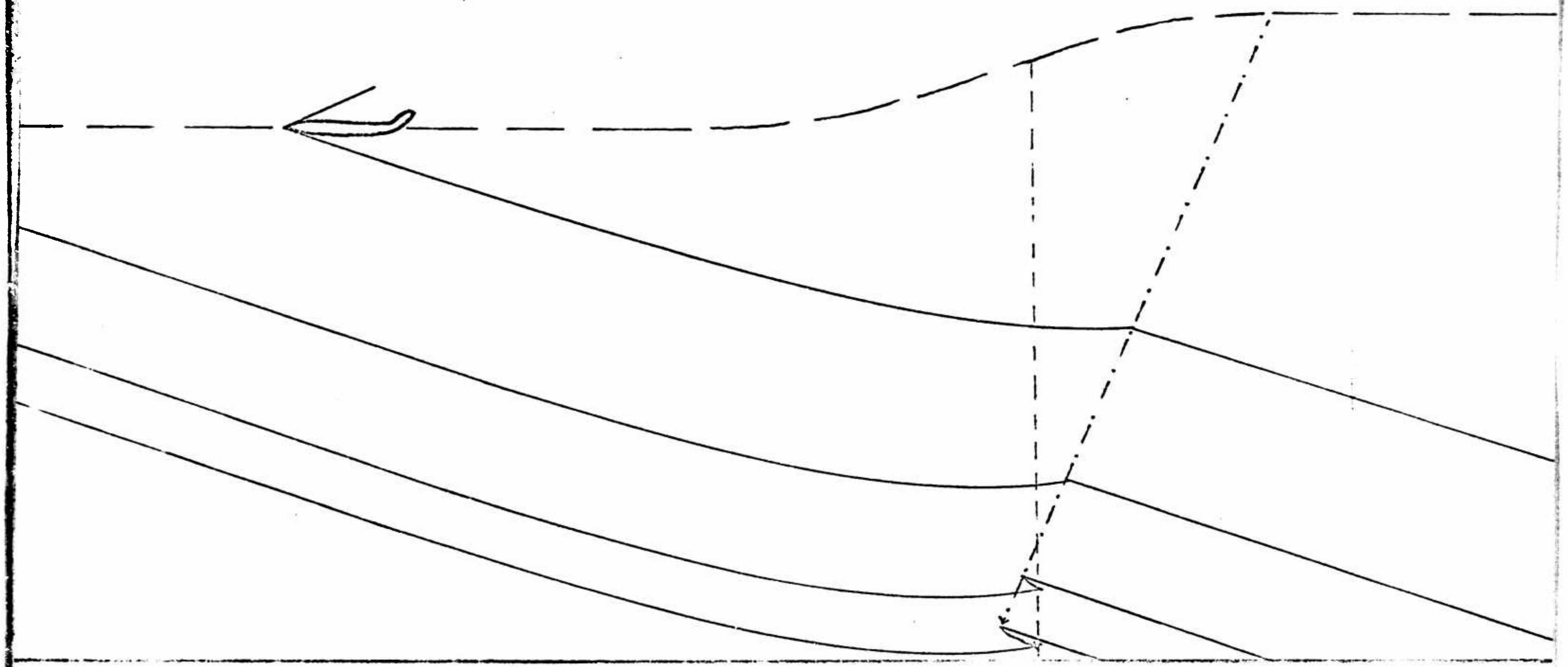

FIGURE 24. Diagram showing the reinforcement of the shock wave caused by a "pushover" maneuver in descent.

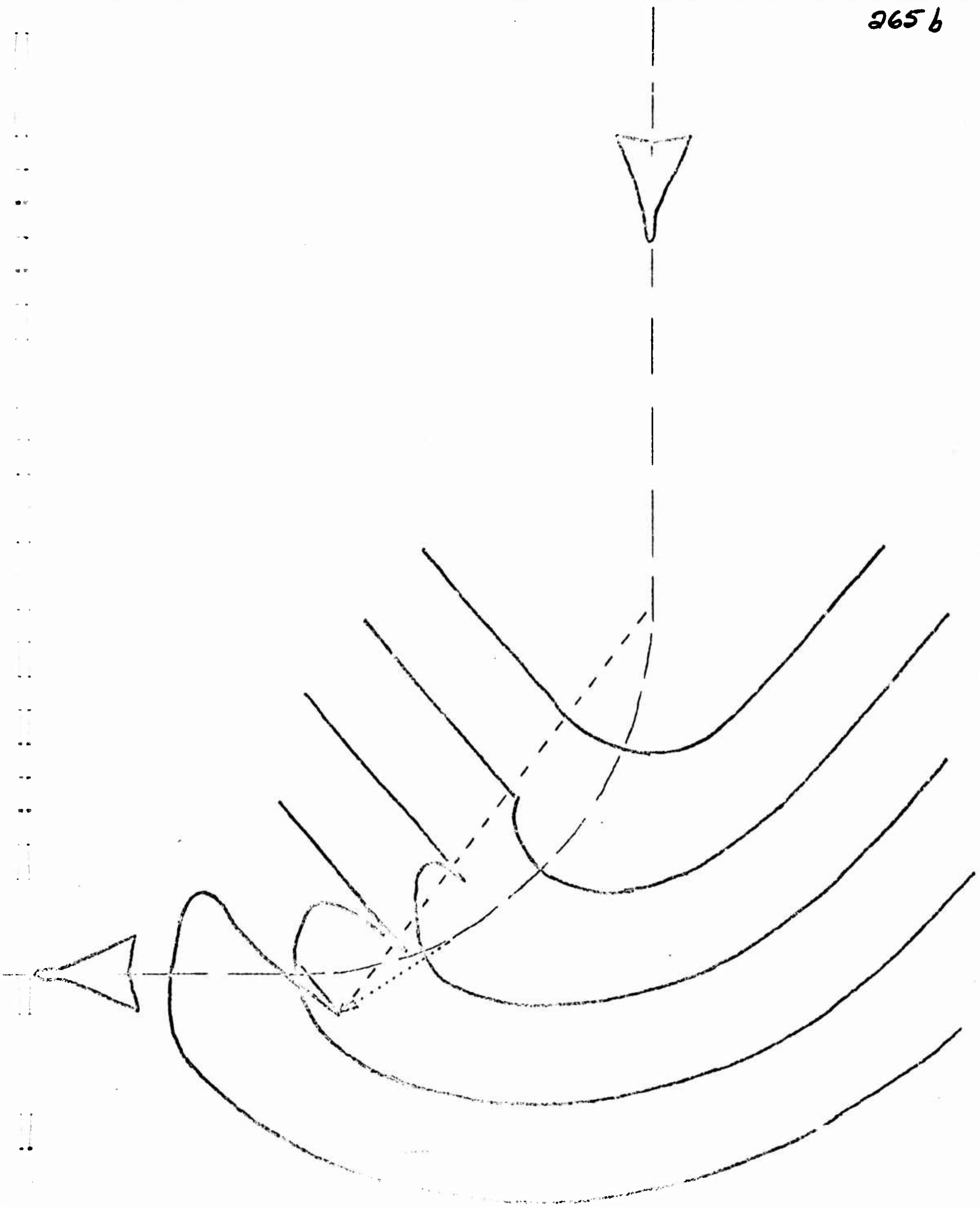

FIGURE 25. View from above the supersonic aircraft showing a series of intersections of shock waves with the ground at a series of points in time caused by a turning maneuver.

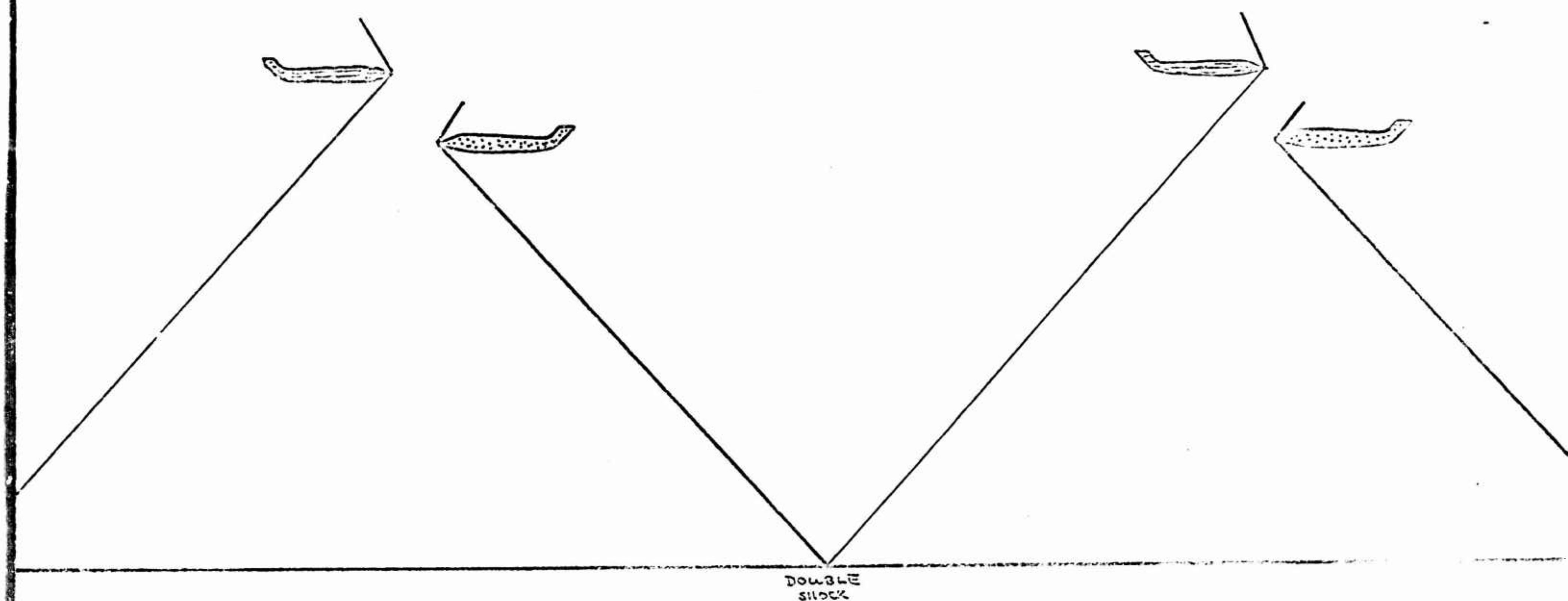

FIGURE 96. Diagram showing the double strength shock wave produced from simultaneous ground intersection of shock waves produced by passing supersonic transports.

time if the planes are close enough together. Although traveling in different directions, the energy of these shock waves will add, causing an amplified shock wave on the ground. A similar effect is created by one supersonic transport overtaking another, as shown in Figure 27. Indeed, in this latter case, the relative speeds and altitudes of the two aircraft may coincide in such a way that this simultaneous intersection at ground level will occur for many miles along the flight path, thus affecting a widespread area with a magnified shock wave.

The magnifications caused in a single shock wave by maneuvers are independent of magnifications caused by the atmosphere, and therefore the effects can be additive. If a shock wave, strengthened because of some maneuver, also encounters distorting atmospheric conditions, threefold and fourfold magnifications become entirely possible.[33] Similarly, the combination of maneuver-amplified shock waves from two different planes could result in eightfold magnification under distorting atmospheric conditions. However the relative predictability of maneuver magnifications should make it possible in most cases to avoid these extremely large factors of reinforcement by using routes and schedules which will avoid overlapping of shock waves produced by critical maneuvers.

3. Reflections.

The magnifications of the shock waves from the supersonic transport which have thus far been discussed occur independently of the ground which the shock wave strikes. Unfortunately, the character of the ground--buildings, hills, lakes, and so forth--also influence the effective strength of a shock wave which strikes a particular person or structure. It has been found that nearly 90 percent of the energy of a shock wave is reflected by smooth surfaces such as water, paved areas, fields,

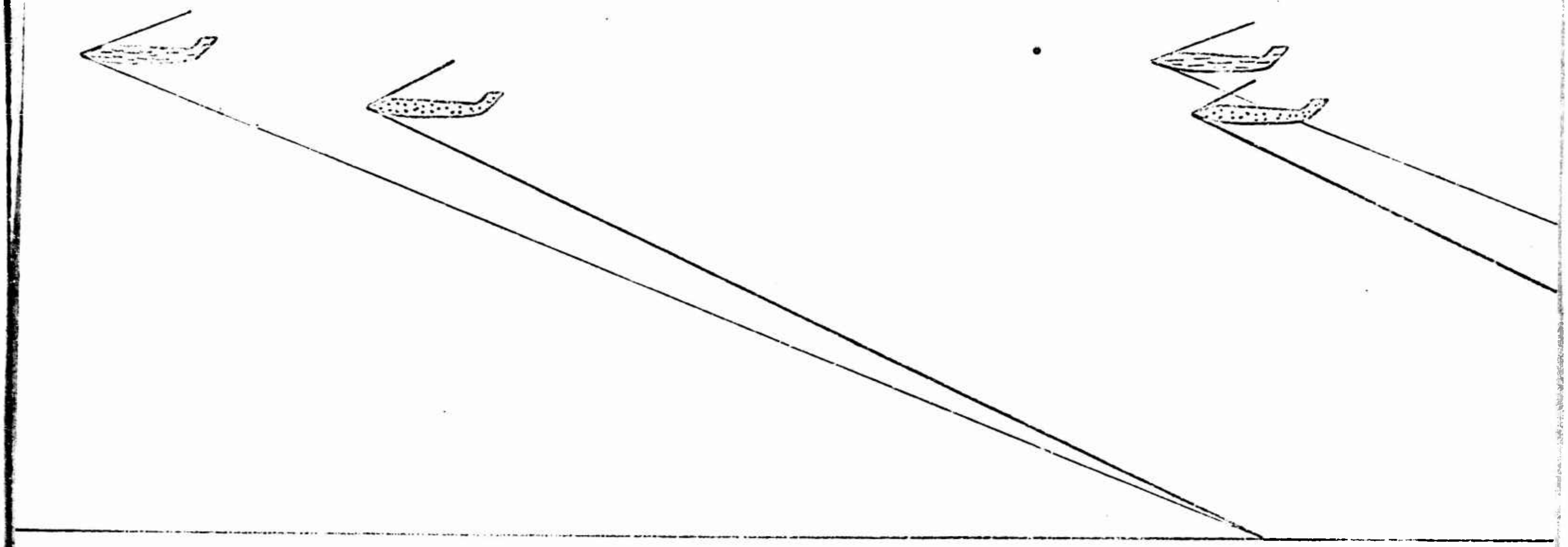

FIGURE 27. Diagram showing the double strength shock wave produced from simultaneous ground intersection of shock waves produced by two supersonic transports where one has overtaken and passed the other.

or walls.[34] Therefore increases in the destructive strength of a shock wave hitting the ground at a particular place may be caused by the simultaneous impact of a reflected shock wave.

Figure 28 shows in a simplified manner how a single shock wave may be reflected upon itself so as to add with itself to form a momentarily magnified shock wave.[35] Anything at the place where the addition occurs (marked by the rough line) would be affected by a double strength shock wave.

The coming together of two shock waves from opposite directions does result in a cumulation of their individual strengths along the line of collision of the two fronts just as two water waves thus colliding will cumulate to form a single higher wave. But the resultant phenomenon is not as dangerous as if a single wave of double strength had been created by the plane; for unlike the plane-generated wave and the other instances of magnification that have been examined, the collision-generated wave has no momentum. A region of doubly high pressure is created along the line of the two shock wave fronts. And any object or person situated at that line would experience the double pressure. But the phenomenon is momentary and then dissipates; it does not form a new, doubly strong shock wave moving at sonic speed that will strike anything in its path.

A potentially more destructive addition of reflected shock waves is shown by the reflection effect of the two buildings in Figure 29. In this case, at least part of one of the buildings may be subjected to the double pressure. Of course, reflections off hills as well as buildings can cause an addition effect with a shock wave as shown in Figures 30 and 31. Comparing these two figures, we see that shock waves

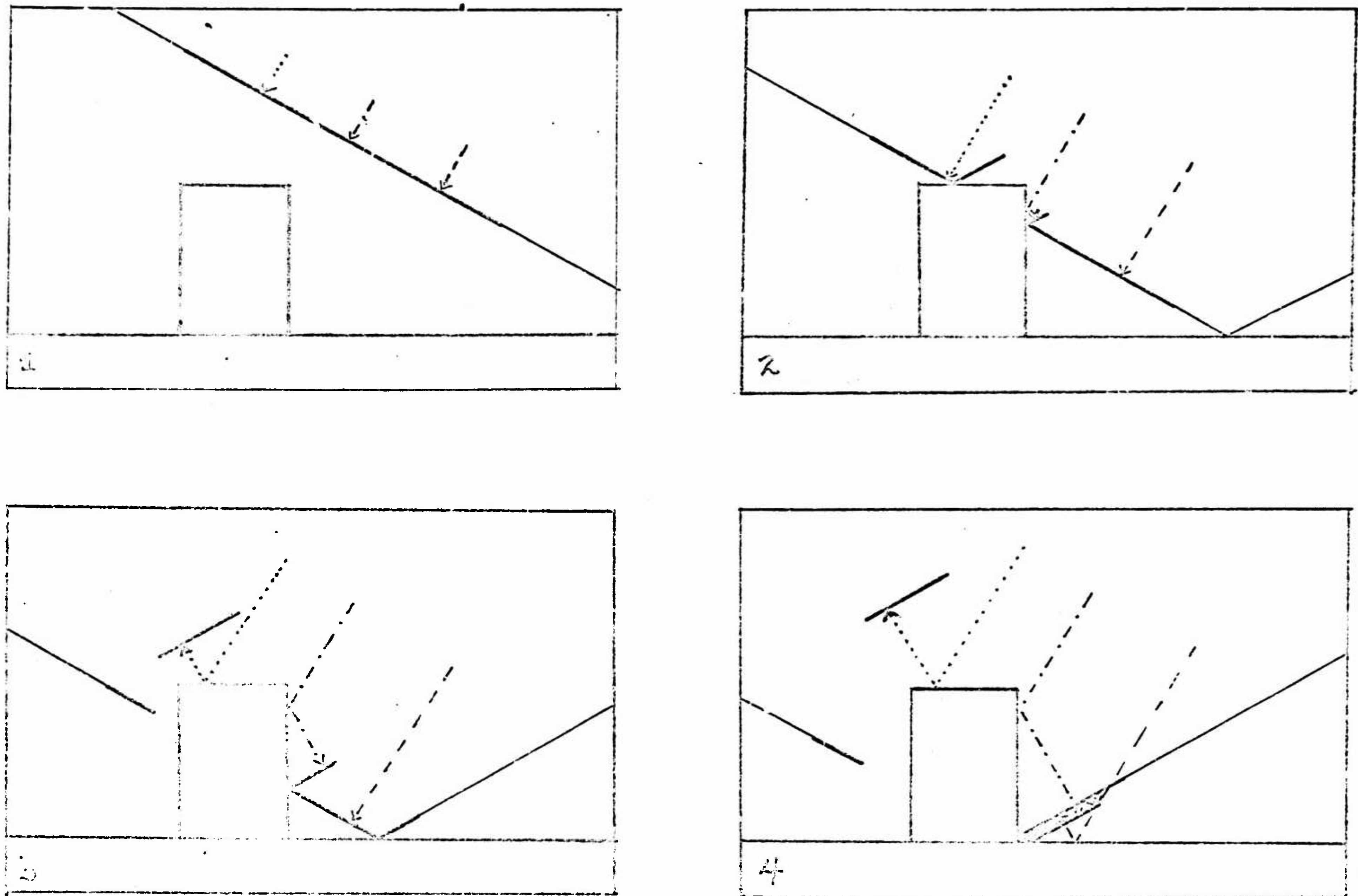

FIGURE 26. Diagrams showing the single reflection of a single shock wave from the ground and a building. The jagged line in (4) shows the location of reinforcement caused by the intersection of reflected shock waves.

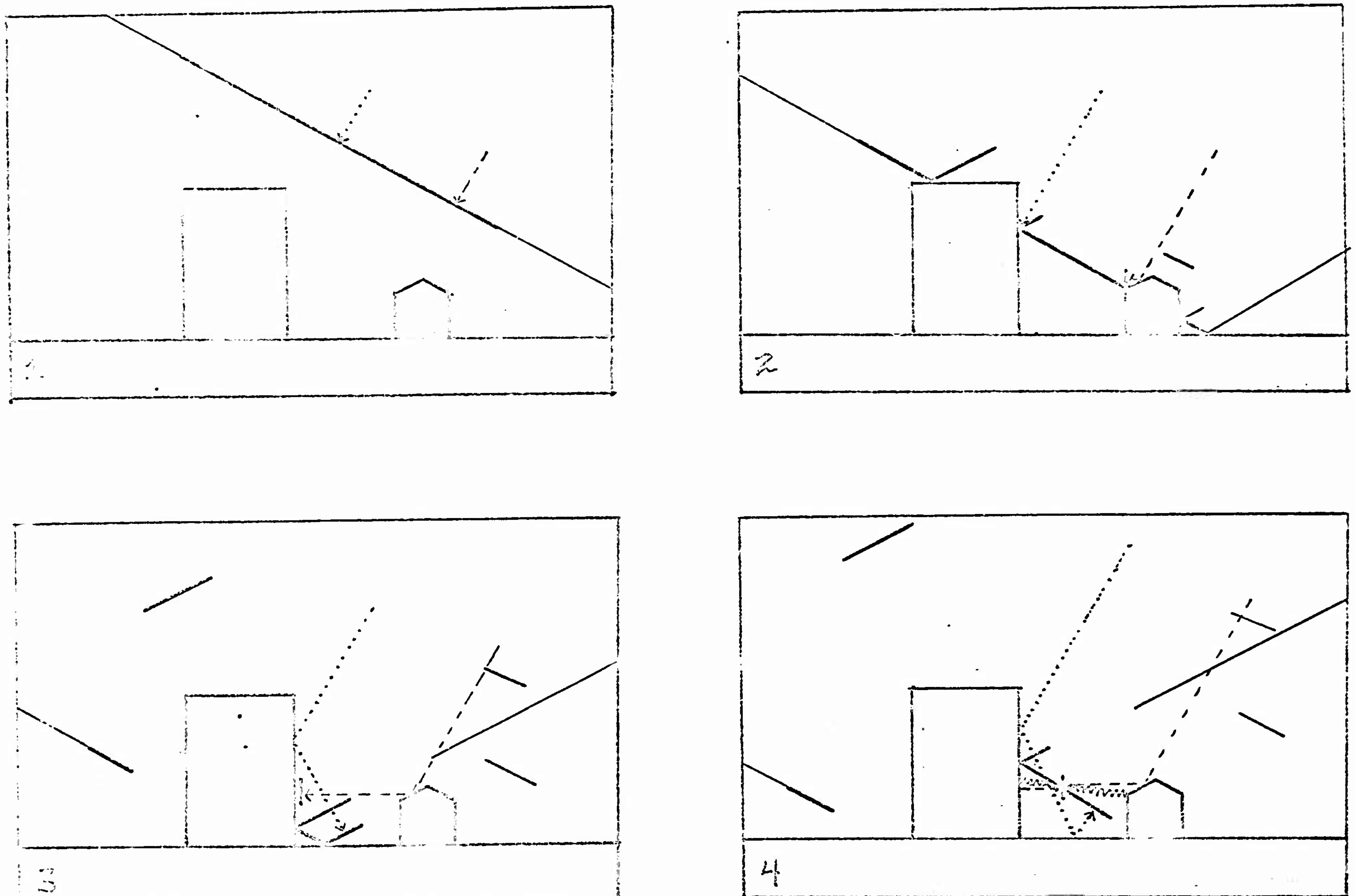

FIGURE 29. Diagrams showing the reflection of a single shock wave from the ground and two buildings on opposite sides of a street. The jagged line in (4) shows the location of reinforcement caused by the intersection of reflected shock waves.

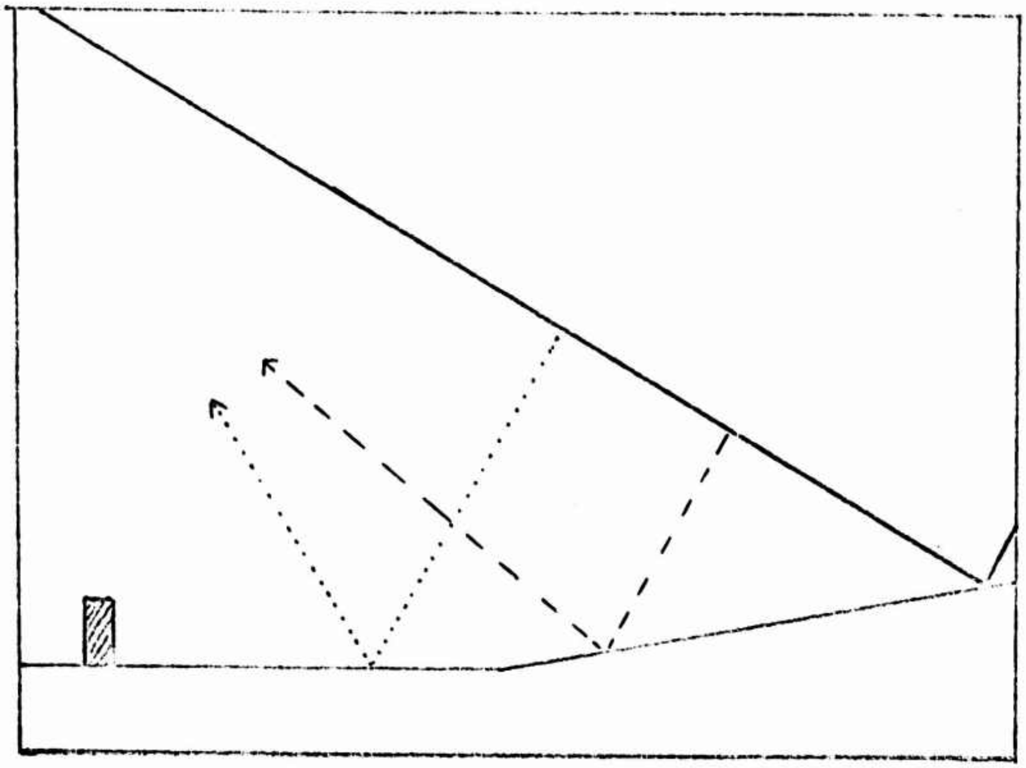

FIGURE 30. Diagram showing the reflection of a single shock wave from hilly ground.

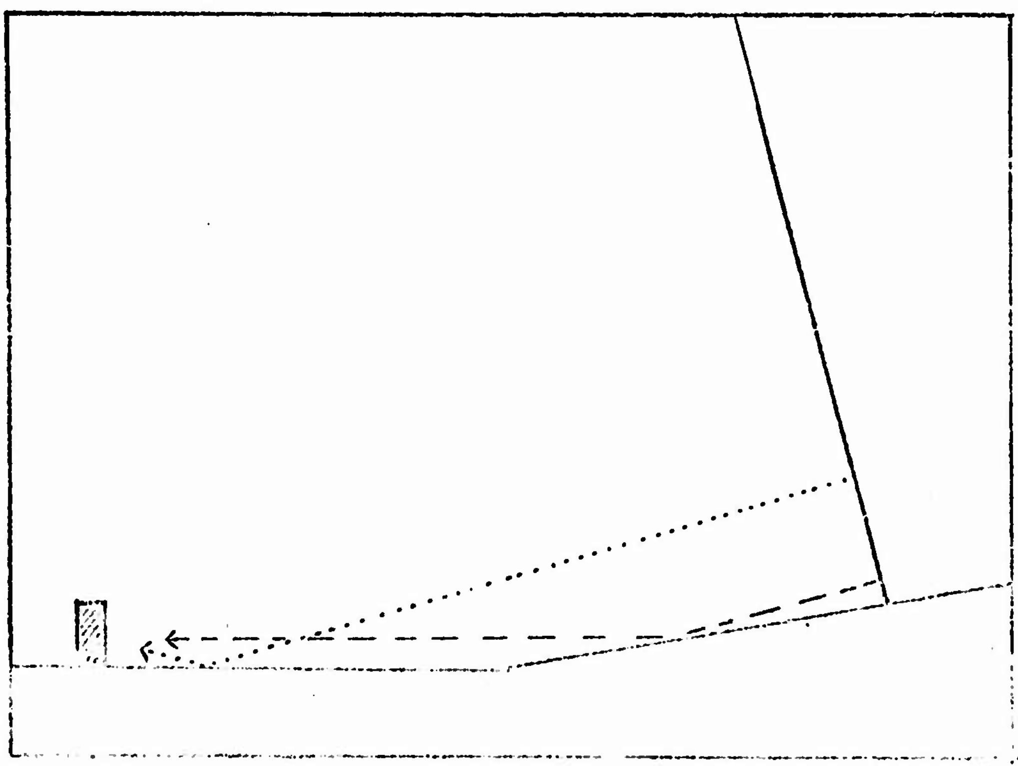

FIGURE 31. Diagram showing the reflection of a single shock wave striking hilly ground at an angle close to the grazing angle.

which intersect the ground at rather shallow angles are more likely to involve additions which actually affect buildings and persons because of the intersection's closeness to the ground.[36]

The supersonic transport will cause two shock waves which will strike any given point on the ground about 0.3 seconds apart. There is very little in the scientific literature on the precise interactions that the two waves will have. It is possible, for example, that the reflected bow wave coming up off the ground will tend to minimize, close to the surface of the earth, the impact of the following tail wave by "filling in" the low pressure region between the two waves.

Even assuming the foregoing speculation is correct, the upper portions of all taller structures will be struck first by the bow wave and then by the tail wave before the reflected bow wave has had an opportunity to weaken the tail wave. If the speculation is incorrect, all objects will be struck sequentially by the two waves. These closely spaced subjections to pressure will cause a resonance effect if the time lag between the two waves is equal to the natural vibration frequency of the object struck or a whole multiple of that frequency.

Suppose, as is illustrated in Figure 32, a window in a tall building is struck by the bow wave and flexes inward under that shock. Hundredths of a second later the bow wave has passed and the pressure outside the building is now lower than that inside. The window flexes back, bowing outside, because of its natural period of vibration and because of the pressure differential. Then, as it starts once more to reverse its direction of flex, it is struck by the tail wave. The second inward flex will be of a greater magnitude than if the tail wave had not struck it at that moment; and the window may break although

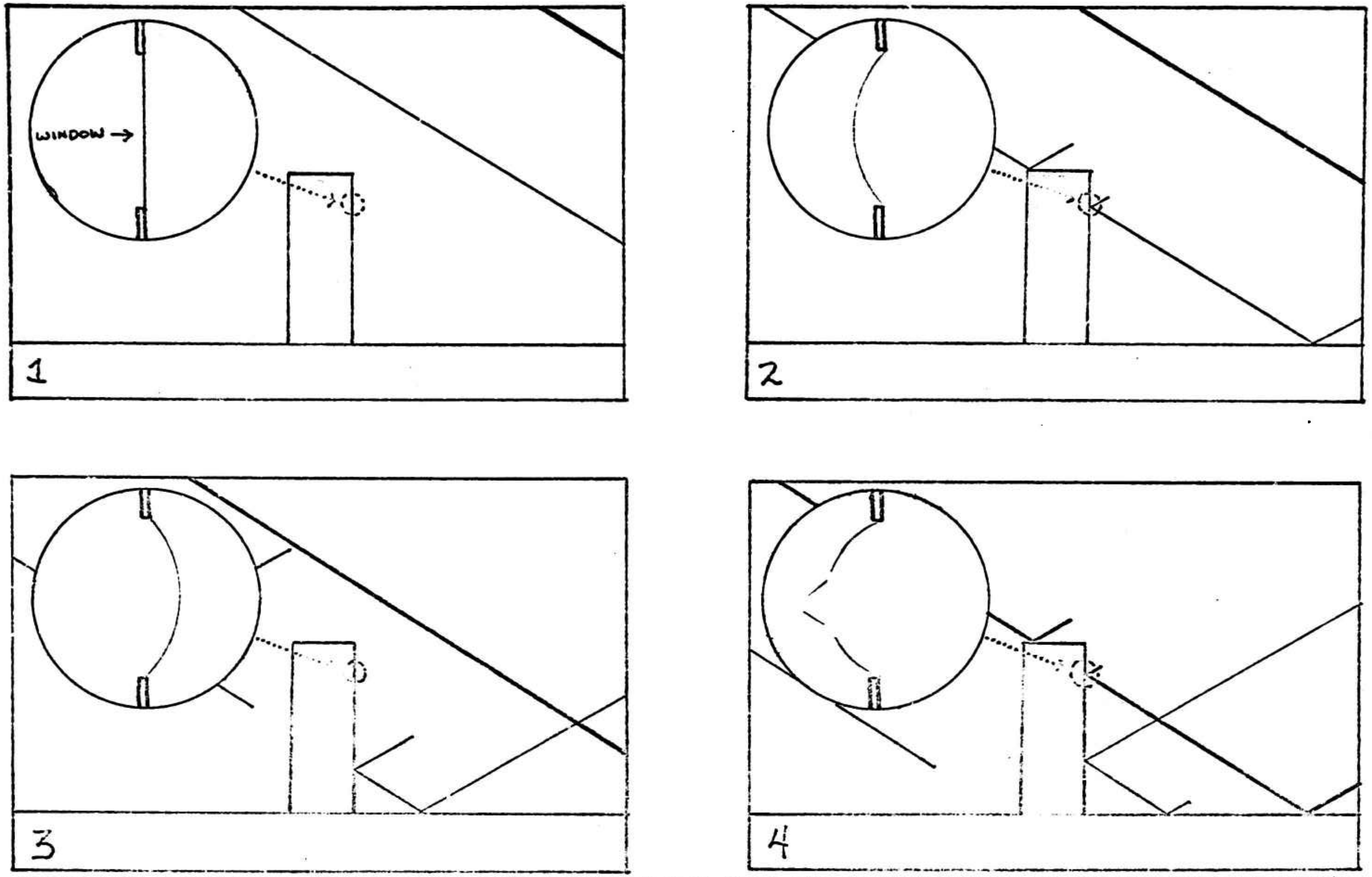

FIGURE 32. Diagrams showing the effect of bow and tail waves on a window which is resonant with the two waves. Figure 2 shows the window's response to the first wave, figure 3 shows the first vibration of the window, and figure 4 shows the response when the tail wave strikes the window during its second vibration in the same direction as the shock wave travels.

neither the bow wave nor the tail wave alone would have broken it. It is not necessary that the natural period of vibration of the window be 0.3 seconds in order for this effect to occur. If its period of vibration is 0.15 seconds, 0.1 seconds, or 0.075 seconds (1/2 or 1/3 or 1/4 the shock wave interval), resonance will also occur.

Since these shock waves follow each other very closely, if one of them is focused either by maneuvers or by atmospheric conditions, the other is likely to be focused. Thus, vibrational amplification because of resonance caused by these focused shock waves may prove to be a serious problem.

C. Sonic Boom Effects

With this analysis of the possible variations in the effective strengths of shock waves from supersonic transports, our attention must now be directed to the nature of damage that may be caused by these shock waves. Two broad categories of direct harm may be involved--physical damage to property and psychological damage to persons.

1. Physical Damage.

The extent of physical damage to property that will occur depends not only upon the overpressure (amplitude) of the effective shock wave, but also upon the sharpness in the pressure rise, the time duration between successive shock waves (including reflections), and multiple recurrences of shock waves over long periods of time.

Certainly the most obvious measurement of the potential destructive power of the shock wave from a supersonic transport is the overpressure associated with the wave, and accordingly, experiments have strongly emphasized this aspect of the shock wave. Indeed, great efforts

have been made to design the American supersonic transport so that the average overpressure of shock waves which reach the ground under ordinary conditions will be less than 2.0 psf (pounds per square foot).[37] But even shock waves having an average overpressure of 2.0 psf will be magnified, in some percentage of cases, to produce effective localized shock strengths of at least 4 to 8 psf. Unfortunately, thus far the best design of the Boeing supersonic transport indicates that the average overpressures will be closer to 3 psf with correspondingly higher effective localized shock strengths. Extensive effort is still being expended to improve this result.[38]

Recent experiments which have been conducted to test the shock wave resistance of glass windows, plaster, and structural building components have indicated that very high overpressures are required for a single shock wave to create damage when the glass, plaster, or structures are free of stresses.[39] For example, overpressures in the range of 13 to 20 psf were required to fracture newly and expertly installed glass windows and to crack newly and expertly plastered walls. Similar overpressures did no ascertainable damage to the structural components.[40] However, much less strong pressures are required to produce damage when stresses are present. It is clear beyond dispute that the St. Louis test, which had no measured overpressures greater than 3.1 psf, caused glass damage. Since the sources of these stresses range from warping and drying of materials over a period of time to imperfect workmanship of the original contractor, probably the majority of structures in this country have significant stresses in one part or another. Therefore, the mere fact that stresses are required for damage to be produced by shock waves having overpressures of 2 to 4 psf does not negate the possibility of widespread damage from such shock waves.[41]

In addition to the overpressure, the sharpness of the rise in pressure is an important determinant of the extent of property destruction. For a single shock wave with a given overpressure, the sharper the pressure rise, the more likely it is that damage will be caused. A sharp pressure rise is more destructive because the structure cannot respond and "give" a little before the full pressure of the shock is upon it. An analogous effect is the common experience that a gradual push against a window is not likely to break it, but a sharp blow from a baseball will be disastrous. Therefore the common requirement of local ordinances that structures be designed to withstand substantial wind pressures (e.g., 20 psf) does not guarantee that structures meeting this requirement will be immune to damage from shock waves having overpressures as low as 2 psf.

The sharpness of the rise in pressure will vary considerably because of atmospheric variations; so it is doubtful that an aircraft with any given characteristics will consistently produce shock waves with relatively gradual pressure rises. Figure 33 shows the wide variation in pressure rises caused by a single type of plane and recorded during tests in Chicago.

A third factor which affects the destructive nature of shock waves produced from supersonic aircraft is the time difference between successive shock waves. If this time difference corresponds to the natural vibrational frequency of the object which is hit by the shock waves, the object will vibrate strongly just as if it were "in tune" with the shock waves. This is the same kind of phenomenon that creates ringing champagne glasses when an opera singer hits the proper note. Just as sustained vibrations may cause the champagne glass to break, so sustained vibrations of the object struck by the shock wave may cause permanent damage to the

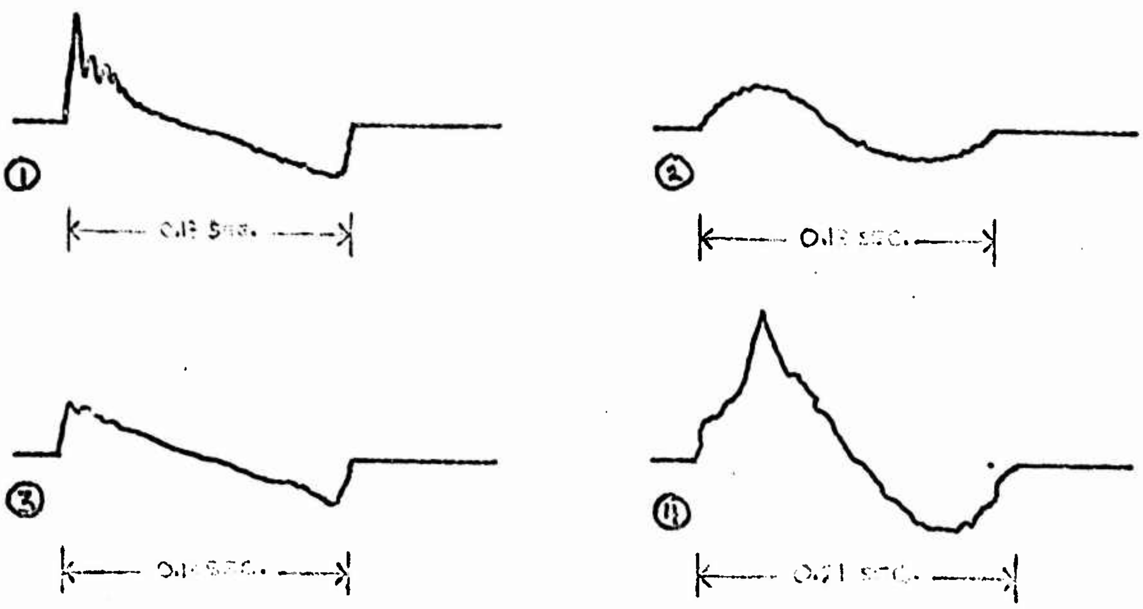

FIGURE 33. Shock wave pressure signatures recorded from flights of B-58 bombers over Chicago in 1965. The signature was subject to change at least every two hours.

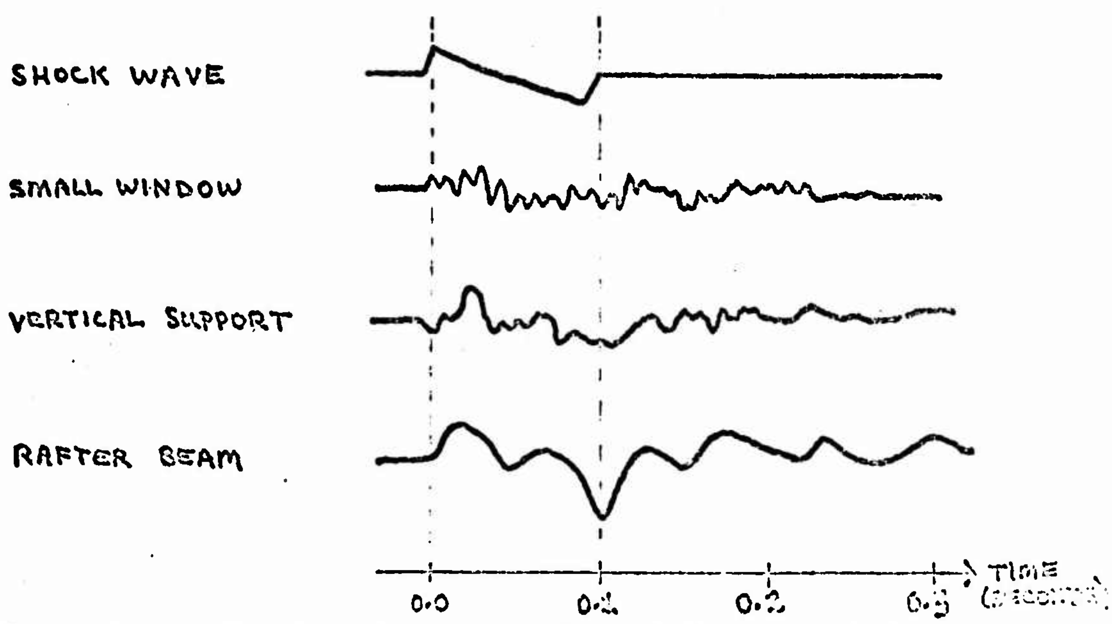

FIGURE 34. Recordings of vibrations caused in different parts of a building subjected to shock waves from a supersonic aircraft. A marked resonance effect is observable in the rafter beam and, to a lesser degree, in the vertical support.

object. The pressure peaks of the front and tail shock waves of the supersonic transport will probably fall in the 2 to 10 cycles per second frequency range, a range that corresponds to the natural vibration frequency of many windows, walls, and beams in common buildings. Although our ears cannot hear this frequency of sound, the building components do "hear" it and react accordingly. Examples of the vibrations set up in a window pane, a wall, and a beam by the front and tail shock waves from a typical supersonic aircraft are shown in Figure 34. The time duration between the two shock waves corresponded to the natural frequency of the beam and therefore the large vibrations shown in that figure were created.

Up to this time no experiments have run long enough or have involved sufficiently frequent flights to indicate the possibility of cumulative damage from vibrations caused by repeated exposures to shock waves from supersonic aircraft. However, extensive experience with other potentially destructive forces has indicated that, although a single shock of a given strength is required to create particular damage, repeated exposure to forces only one tenth as great will eventually cause the same damage.[42] Therefore, it is possible that the cumulative effect of five or ten years of daily exposure to even the ordinary shock waves from the supersonic transport will prove to be a substantial source of physical damage.

2. Effect on People

Although there has been speculation that physiological harm might be done to persons by the direct force of the shock wave, experiments have shown conclusively that no probable shock wave produced by a supersonic airplane will be strong enough to rupture eardrums, the part of the body most sensitive to shock wave pressure.[43]

But the shock wave is perceived as a very loud and sudden noise. The loudness of shock waves striking a person directly depends upon the overall configuration of each shock wave and the time differential between successive waves. The higher the overpressure of the shock wave, the louder it seems, although our senses cannot readily distinguish the difference in loudness between two waves having overpressures differing by only 1 psf. A sharp rise in the pressure makes the shock wave seem louder than a wave characterized by a gradual rise in pressure. Perhaps most important, the higher the average frequency of the sound waves which make up the shock wave, the larger a fraction of the energy actually present is perceptible by the human ear and the louder the noise seems.[44] The average frequency for supersonic transports will actually be lower than the average for present day fighter aircraft; but since the range of frequencies is very broad, a substantial part of the wave's energy will lie in sound frequencies within the audible range.[45]

In addition to these characteristics of a single shock wave, the time differential between successive waves is important. The human ear can not distinguish between shock waves which are less than 0.05 seconds apart. Although the ear responds almost immediately to the first shock wave, any other wave which may strike the ear within 0.05 seconds is perceived as an augmentation of the first wave.

The effect of a shock wave on a person's sensations also depends critically upon where he happens to be when the shock wave hits. If he is standing in an open field, only the shock wave, its reflection, and the shaking of the ground itself (caused by the widespread impact of the shock wave) give him a sensation of noise or discomfort. If he is standing near buildings, he is affected by

multiple reflections rather than a single reflection. Multiple reflections within the 0.05 seconds may create an apparent loudness several times as great as that sensed by a person standing in a field who hears the same wave.

If a person is inside a building when the shock wave strikes, vibrations caused by the jarring of the building will be felt; and these vibrations last much longer than the shock wave itself. This oscillation of walls or window panes also sets up secondary sound waves as shown in Figure 35, and the resonance created by these secondary waves in a closed room can be substantial. On the other hand, if the room is open to the air, the shock wave may enter directly into the room and be reflected inside it as illustrated in Figure 36. This also results in resonance in the room, thereby making the effective noise seem louder than if it had been experienced in an open field. A recent study has indicated that the same shock wave seems twice as loud when heard inside as when heard outside.[46]

The primary significance of the apparent loudness of the sonic boom is its startle effect on people. With respect to its capacity to startle, a sonic boom is very different from the noise associated with subsonic aircraft. Noise from a subsonic plane is heard before it reaches full intensity and thus furnishes its own warning of louder noise to come. The full impact of the sonic boom is upon the observer before his senses can perceive any indication of its arrival. Neither the shock wave nor the cruising supersonic transport from which it originates will be seen or heard before the full impact occurs.

There is substantial controversy regarding whether people will become accustomed to hearing sonic booms and therefore will not be startled

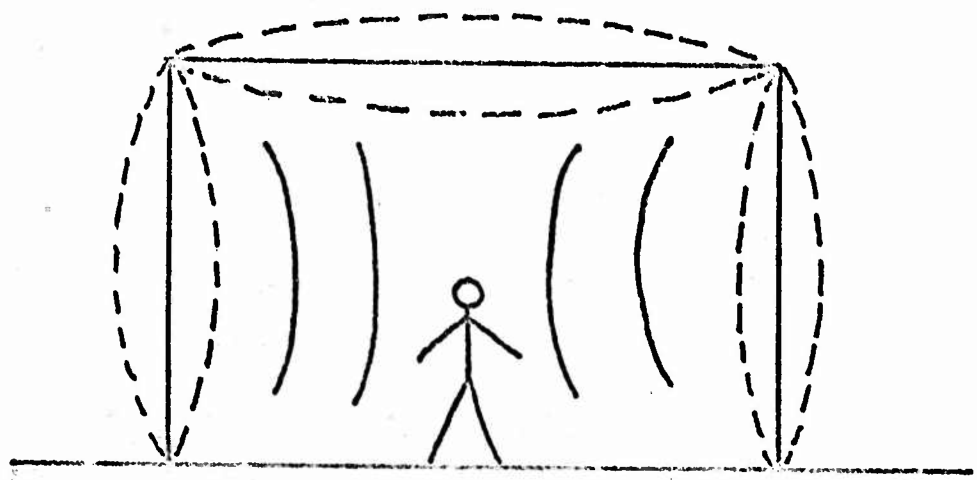

FIGURE 35. Diagram showing the resonance caused in a closed room by vibrations from walls, ceilings, and windows as a result of a shock wave striking the building.

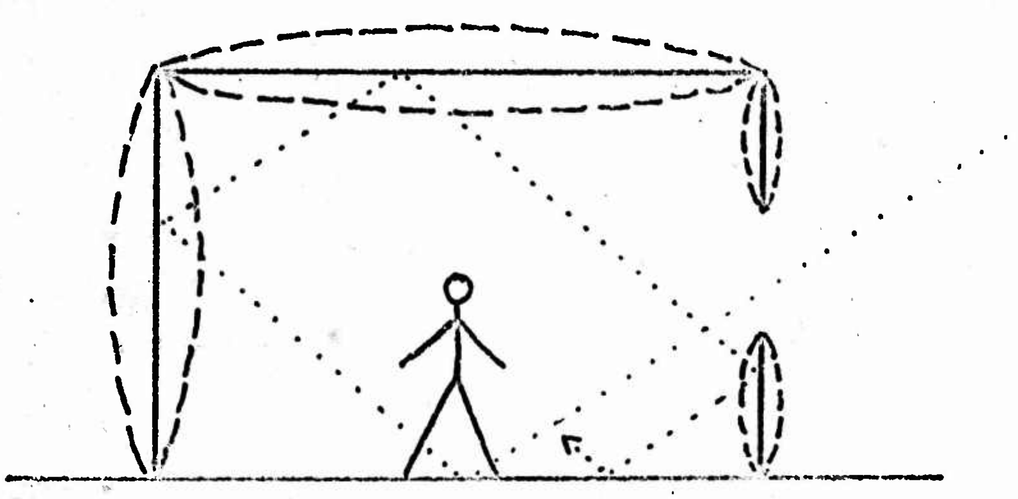

FIGURE 36. Diagram showing the resonance caused in an open room by reflections from a shock wave entering the room directly. Resonance is also caused here by vibrations in the walls and ceiling.

when booms become common. A division of commentators into two camps has occurred--the "no-startle" group and the "startle" group-- and each side interprets very differently the experimental data that are available.

The first types of experimental data cited are laboratory experiments in which volunteers have been subjected repeatedly to recordings of sonic booms or other like noises during the short period of time comprising the test. The no-startle group cites a set of results which indicated that a noise designed to be the equivalent of a 2 psf shock wave produced no physiological startle (measured by the heart rate) after the first exposure during the test.[47] But the startle group rejects the inferences that might be drawn from such tests on several grounds: The test did not involve the strong building vibration which a real shock wave causes. The volunteers were all young, healthy and alert persons. Under the circumstances only the first simulated sonic boom could be expected to cause a startle effect because the subjects knew that what they were experiencing was only a test and expected subsequent booms (the time span of the test was ten minutes). Finally, several of the subjects were startled by the first exposure and experienced a significant jump in heart rate.

The startle group cites a different laboratory experiment which indicated that the upper limit of acceptable shock waves as heard indoors is 1.0 psf and as heard outdoors is 1.9 psf.[48] However, the no-startle group points out that although the relative acceptability between indoor and outdoor shock waves may be correct, the method of determining the quantitative values of the overpressure was sheer guesswork.

None of these laboratory experiments can be regarded as affording substantial evidence of the significance or potential for harm of the startle effect, especially with respect to sleeping or sensitive persons. It seems fair to analogize experiments conducted thus far to testing reactions at a fireworks display for the purpose of learning whether a man is likely to be startled by the unexpected explosion of a cherry bomb under his bed.

The second type of experimental data cited by the opposing groups in this controversy involves public reactions to actual sonic booms produced in tests conducted with Air Force planes over populated areas.[49] The no-startle group notes that the number of complaints received in these tests was small compared to the number of persons exposed to the shock wave.[50] However, in opposition, the startle group argues that most people generally are reluctant to make formal complaints and that public opinion polls are a better guide to the true reaction of persons subjected to the booms. They note that a poll conducted shortly after the St. Louis test showed that 74 percent of the people experienced startle reactions and 31 percent found the startle to be annoying.[51] The no-startle group counters with the observation that polls after the tests in Oklahoma City showed that a person's willingness to accept sonic booms was highly correlated with his attitude toward the SST program.[52] But the startle group points out that the same polls show that, even of persons with the <u>most</u> favorable attitude, eight percent said they could not accept eight sonic booms daily.[53]

Buried among these statistics from the Air Force tests are several undisputed facts: First, the shock wave overpressures reaching the ground under the flight path ranged from about one-half the average

expected for the SST to a maximum about equal to the SST average. There were no booms as loud as some the SST will create. Second, the widths of the areas affected by each flight were probably less than two-thirds the width of the SST boom carpet. Certainly the total area involved was far less than the area which would be affected by an equal number of SST flights. And third, the tests created clearly defined adverse reactions from a significant fraction of the population. Although the significance of the fact is somewhat obscured by political factors, reaction to the Oklahoma City tests was sufficiently adverse to lead the City Council to request that the tests be terminated before their scheduled completion.[54]

In the case of greatly magnified shock waves (superbooms), even persons not sensitive to ordinary booms may have a startle reaction, for the relative infrequency of such shock waves will not permit people to become accustomed to them.

The magnitude of the startle reaction is an important question not only because people dislike being startled but because the phenomenon can be expected to cause a certain number of serious physical injuries. Damage claims filed with the Air Force include a number for injuries thus caused.[55] Persons startled while they are performing various physical activities may suffer such injuries as falls from ladders, falls down stairs, cuts from power-tools and similar consequences of human malfunction.

There is no reliable information at the present time indicating the probable effects of repeated exposure to booms over long periods of time on psychological health.

Somewhat related to startle effect and psychological effect on persons is the effect booms may have upon domestic animals and the

industries dependent upon those animals. Experimental studies have not concentrated upon this aspect of the sonic boom and no significant data is available. Effect on animals may prove to be a significant problem, however; the six month Oklahoma City test indicated that at least some people believed the sonic booms had an adverse effect on production from animals upon which their business depended. Claims have been filed with the Air Force for many varieties of damage to animals,[56] including baby minks killed by their mothers, chickens that huddled in a corner of a coop and smothered and horses that stampeded into barbed wire -- all assertedly in response to booms.

3. Extent of Exposure to Booms

Having described the possible effects created at particular places on the ground by shock waves generated in supersonic flight, we turn our attention to the extent of exposure to these effects on the assumption that transcontinental flights by supersonic transports will become a common part of air transportation. Because each supersonic flight creates shock waves which affect an area of the ground at least 50 miles wide and extending along all but the very beginning and end of the flight path, regular supersonic flights will affect large areas of the country. All of the area shaded in Figure 37 would be exposed to sonic booms by just one one-way flight between each pair of cities more than 1500 miles apart and having a population in the vicinity of each city of more than one million. That figure represents a conservative estimate, since it includes no foreign flights, no domestic flights of less than 1500 miles, and no flight to or from a metropolitan area with less than one million population. One such set of round-trip flights would expose the same or a very similar area twice, and so on for each set of flights.

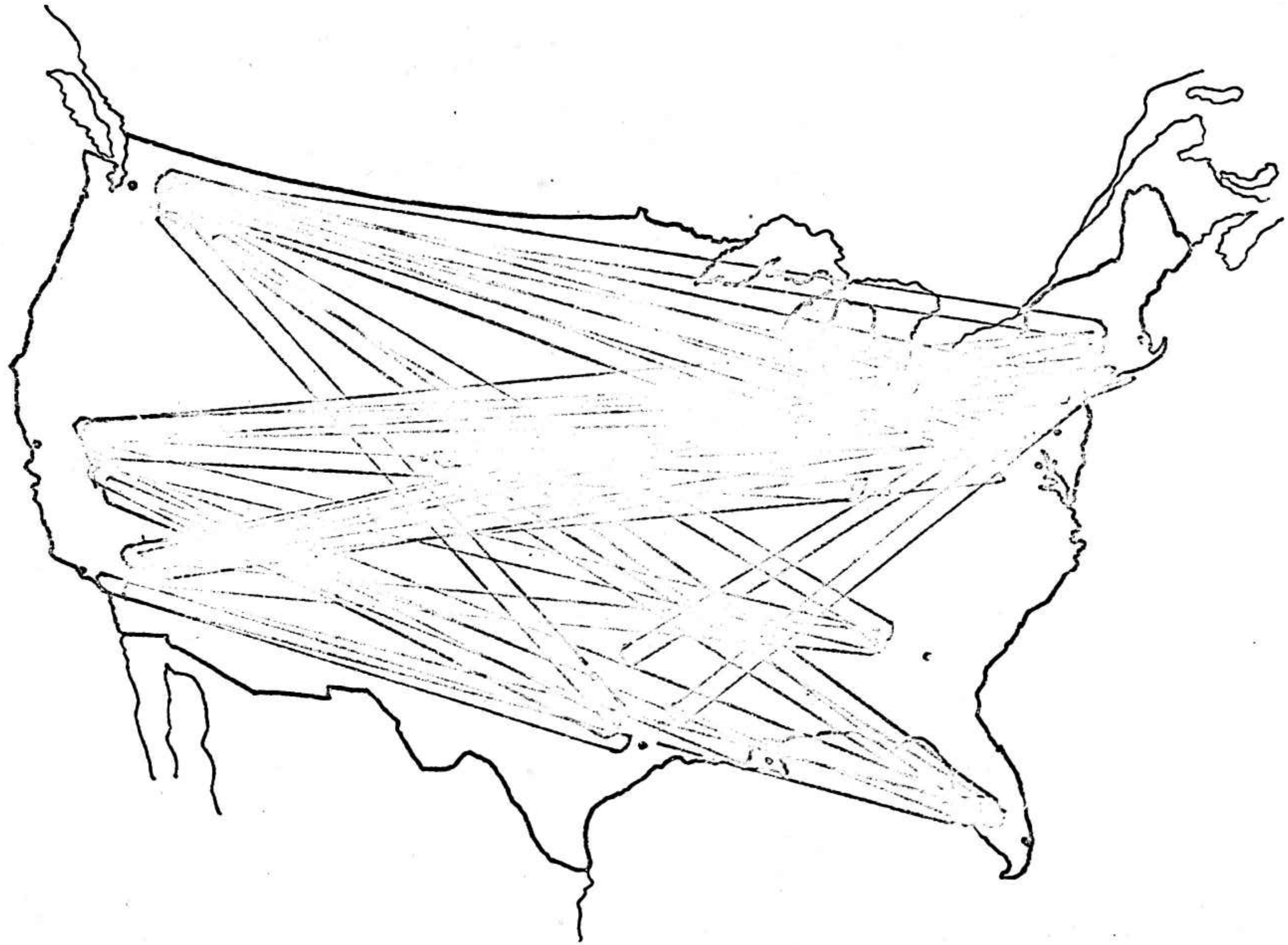

FIGURE 37. Map of the United States showing the areas that will be affected by sonic booms from supersonic transports if the transports are used between metropolitan areas having populations greater than one million and lying greater than 1500 air miles apart (shaded area). Only domestic flights are included here.

The implications of this exposure may be illustrated by the case of the Los Angeles-New York run. The area exposed includes at the present time more than 10 million people. If 10 flights occurred every day in each direction, each of the 10 million people will be exposed to 20 booms each day, 7,300 booms each year. Seventy-three billion person-exposures per year would be caused by this one run. Although double-strength booms occur only one time out of 1,000, 73 million exposures to double overpressures would occur each year as a result of flights between these two cities.[57] This estimate is conservative in that it makes no allowance for shock wave magnifications caused by aircraft with crossing paths or for aircraft passing or overtaking one another.

Part II: THE SONIC BOOM

Chapter II: THE LEGAL ASPECTS

A. The General Analysis:

The purpose of this chapter is three-fold: 1) to articulate briefly the criteria by which the adequacy of a legal system to deal with sonic boom damage may be judged; 2) to discover the various theories of relief which might be available under present law to a plaintiff whose person or property has been damaged by or on account of a sonic boom; and 3) to evaluate these theories and suggest alternative rules that would more nearly satisfy the proposed criteria.

We derive the criteria initially from the same kind of economic analysis which we applied to the problem of airport noise. Sonic boom damage represents a cost that supersonic flight imposes on those who must share the environment into which it intrudes itself. If the benefits that commercial supersonic flight yields are capable of paying these costs as well as all its other costs, then it should be permitted. Once this decision is made and resources are committed to the enterprise of supplying supersonic air transport, then a rational society will take into account the fact that it has a sunk investment in the enterprise of supersonic transport; and it will take such accommodating measures as are economically efficient to minimize the damage that will flow from sonic booms. Such measures might include, for example, mounting all newly installed panes of glass in special mountings. In theory, at least, the division of all affected investment into "pre-existing" and "subsequent" categories would be appropriate. Damage, or loss of value, inflicted on pre-existing investment should be regarded as a cost of supersonic flight and imposed on that enterprise to the dual ends of testing the

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proposition that its benefits exceed its costs and of avoiding unjust, substantial shifts of wealth from those adversely affected by booms to those who receive the benefits of supersonic transport.

As was true in the context of airport noise, the only means by which this comparison of SST costs and benefits can be made with even approximate accuracy is to establish markets in which people can register their displeasure with booms and their pleasure with shorter air travel time. Neither in the airport noise context nor here is there any particular difficulty in establishing markets on which the benefits of air transport can be measured: those benefits are measured with tolerable accuracy by the prices air transport users are willing to pay for the transport service. The disutility of airport noise could be measured by the means we outlined in the prior portion of this report. Those means may be characterized as devices for asking people how much more they are willing to pay to carry on their lives in areas free from airport noise rather than in areas subject to such noise. Their answer to that question is revealed by the difference in rental value between properties in the same general area and otherwise similar except for the exposure of one property to aircraft noise.

No similarly reliable index of the social disutility of the sonic boom will exist. Exposure to the boom will be common to very large areas, leaving no areas unaffected which are sufficiently similar in their geographic features to furnish a standard of value comparison. If it were possible to find a measuring device similar to differentials in rental values around airports which could be looked to as a source of quantitative information about the disutility of booms, we would be strongly disposed to urge that a market solution to the sonic boom problem be adopted: in our opinion, the history of our institutions shows quite plainly that legal systems cannot be administered successfully if they depend wholly upon administrative intuition about the comparative

utility of different courses of action. They are unsuccessful in several senses: First, because they lack any objective criteria, such as market data, upon which to base the choices that must be made, the correctness of the choices made is inevitably open to doubt. Second, for want of such criteria, the administrators are unable to justify persuasively the choices they have made. Third, because the choices made cannot be shown objectively to be either right or wrong, the administrators are vulnerable both to the accusation of corruption and to actual corruption. To avoid such administrative institutions whenever possible is a basic dictate of political wisdom.

But avoidance is not always possible; and we do not believe it is possible in the case of the sonic boom. The boom, in this respect, is similar to the phenomenon of automobile noise. Automobiles make noise and thereby lessen the amenities of our environment. Three basic social responses to that fact are conceivable: first, outlaw use of internal combustion vehicles in some or all public places; second, permit their use without restriction; third, permit their use subject to the condition that mufflers are installed. The third choice, of course, permits of an almost infinite variety of sub-choices in terms of how much quieting will be insisted upon at the expense of chemical efficiency; for, in general, the more effective a muffler in terms of noise, the less efficiently, by engineering standards, the engine will run when equipped with the muffler. But efficiency in engineering terms is a far different thing, and employs a far narrower calculus, than economic efficiency: in engineering terms heating with natural gas is vastly more efficient than heating with coal; but if coal is cheap and gas is scarce, the choice of coal is correct on economic and social criteria.

But while few would doubt that we are wise to choose cars with mufflers over the extreme alternatives of no cars or no mufflers, there is no objective criterion available by which to decide how much we should be prepared to pay,

in engineering efficiency, for more thoroughly muffled, quieter cars. To answer that question we would have to establish a market of some sort through which people could buy units of quietness and thus tell us how highly they value quietness in comparison with other goods and services -- in particular, in comparison with cheaper automobile transportation. But the ubiquitousness of the automobile renders any such market impossible. The prospect of hundreds of millions of noise sufferers bargaining with tens of millions of automobile users and making payments to induce the users to install more effective mufflers is absurd. The expense of establishing and maintaining such a market -- the resources that would have to be devoted to make the market do its job -- would surely exceed the benefits that society would derive from obtaining a more nearly correct answer to the "how much muffler" question. And this point, the point at which the administrative expense of getting better answers exceeds the value of better answers, is the point at which substitution of intuitive for objective judgments becomes politically justified.

Like the imperfectly muffled automobile, the SST will expose so many people to its disturbing and often destructive shock waves that any attempt to account for all those costs, ranging from trivial annoyance to serious physical injury, and to require that the aviation industry pay those costs to those upon whom the costs fortuitously fall would be impossible of accomplishment. We stress that it is because the task is impossible, not because it is undesirable, that it shou be abandoned. The costs are no less real and no less enormous by reason of the fact that they cannot, as a practical matter, be reimbursed.

Rather, the implications that should be drawn from the impossibility of achieving a market solution to the boom problem are two: First, those costs of

the boom that can be accounted for -- those that are imposed in sufficiently large chunks on single individuals to make the expense of accounting worthwhile -- should be reimbursed by the SST activity. And second, even after we have taken the first step of transferring accountable costs, the SST will be bearing far less than its actual social costs. It will be imposing substantial externalities upon the community at large. If nothing further is done, too many resources will be devoted to SST activity and too little to all the other activities, such as food, surface transport, education, fire protection and housing, that satisfy human needs. If nothing further is done, improperly large quantities of income (or well-being, or utility, or wealth -- the label is not critical) will be transferred from those many who suffer the booms to those few who choose to fly in the silent vortex of a shock wave.

The second step that should be taken is an administrative step, admittedly intuitive in its judgmental process, that achieves less boom and more tranquility -- a step that serves as a substitute for, an approximation of, all those other costs of the boom for which it was impossible to account through market mechanisms. The essential function of that step is to cut back the extent of sonic booms to that level which would prevail if all the unaccountable costs were being accounted for and imposed on the industry. One way to achieve this -- not necessarily the best way -- would be to make an estimate of the unaccountable costs and to impose costs of that amount on the industry by a tax which, in its impact on individual companies, corresponds as closely as possible with the harm each company does. An example would be an excise tax on SST tickets in an amount proportionate to the product of the number of persons who will be exposed to booms during the trip, times the normal overpressure created by the aircraft type used. A second type of measure -- probably the most obvious -- is a process of FAA aircraft certification: an aircraft that

generates a normal overpressure in excess of some selected value must not be permitted to operate over inhabited areas.

We will proceed within this framework to discuss in detail the two steps that must be taken: first, compensation for substantial injury; and second, supplementary administrative control of the SST.

B. Recovery for Sonic Boom Damage

It is 1977. The Farmer family lives on the outskirts of Quincy in western Illinois. Their farm is subjected daily to at least 100 sonic booms of varying intensity; the routes between a large number of major city-pairs are within sonic-boom range of the farm.[1] Since supersonic flights along these paths began, the Farmers have periodically been forced to replace glass windows that have been cracked; a recent and particularly fierce boom broke nearly half the windows in the greenhouse, and the flying glass severely cut Mrs. Farmer. The family home was recently remodeled, but large plaster cracks have already appeared throughout the house, and the kitchen roof has begun to leak.

It has become nearly impossible for anyone to work in the metal barn because the vibrations and resonance caused by each boom are almost intolerable. Mr. Farmer was seriously injured a short time ago when he was startled by a boom while adjusting the cutting angle of the reaper. Neither the Farmers nor their animals are able any longer to enjoy restful sleep; milk and egg production have declined and the family members are finding it increasingly difficult to perform their chores with their customary efficiency.

This hypothetical family's troubles suggest the various kinds of damage which may be caused, and will be alleged to have been caused, by sonic booms. General weakening of structures may be the result of repeated exposures; breakage of glass will result from a particularly strong boom, especially if the glass has been pre-stressed by imperfect mounting or by settling of the building.

In addition, the boom can have damaging secondary effects, as when a startled person injures himself or when boom-broken glass injures him. What are the prospects for recovery on account of such injuries under present law?

1. Causation

The first and most difficult problem for a plaintiff seeking compensation for sonic boom damage will be that of proving that a particular boom or series of booms was the cause in fact of the damage of which he complains.[2] Whether he seeks recovery under a policy of insurance; whether he rests his case on negligence, trespass, or strict liability as a theory of recovery; or whether he seeks to take advantage of a compensatory scheme established for the sole purpose of making compensation for sonic boom damage, an essential element of his claim will be proof of a causal relation between a sonic boom or booms and the damage. If he is required to proceed under traditional tort theories, he will also have to identify with particularity the airline whose flight generated the boom or booms that did the damage.

Proof of a causal connection between booms and damage will be difficult for two reasons. First, experts disagree about the amount and kind of structural damage which can be caused by various amounts of overpressures.[3] Where the actual occurrence of the damage was observed by the property owner -- where a boom broke a window, for example -- the proof problem will resolve itself principally into an issue of credibility. But where more pervasive structural damage appears to the property owner to be the result not of one boom but of the cumulated effect of many booms over a period of time, he will encounter another difficulty. He will have to show by indirect evidence that, of the variety of circumstances to which the structural default might plausibly be attributable, a series of sonic booms and not some other circumstance

caused the default. Plaster can be cracked by slamming doors and settling foundations, for example, and shingles can be loosened by wind and weather.

Identification of the airplanes which caused the damage will be an insuperable task unless the plaintiff has access to records of either the airlines or the CAB: the SST is expected to cruise at altitudes of 70,000 feet, where it cannot be seen at all by the naked eye of an observer on the ground; and at lower levels of supersonic flight where the plane might be seen, it would not be possible to detect the airline insignia because of the speed of flight. If a prospective plaintiff were claiming that damage had been caused by one boom rather than by a series of booms, and if he had been able to note the precise time of the boom, airline or CAB records often would enable him to identify the plane that most likely caused the boom. If two or more planes were in the vicinity and each could have generated the offending overpressures, and if it is clear that one did in fact cause the damage but the plaintiff is unable to determine which, the plaintiff could argue that he should be relieved of the insuperable burden of proving which was the cause and that joint and several liability may be imposed[4] unless one of the defendants is able to prove that he has not caused the harm.[5] But if a prospective plaintiff is claiming that damage has been caused by the cumulative effect of booms over an extended period of time, and even if he is able to identify the airlines whose planes were probably responsible for the offensive series of booms, he will have great difficulty establishing that any particular airline's booms were a "but for" cause of the accumulated damage; and as the frequency of booms increased, the chances of proving that any one boom was a "substantial factor" in causing the cumulative damage become more remote. Plaintiff's only hope again will lie in the argument -- more tenuous this time in terms of conventional legal principles -- that all the airlines should be held jointly and severally

liable for the damage since he knows that some or all of them caused it but it is impossible for him to make specific identification.

The difficulties inherent in the causation problem are not susceptible of easy solution. Indeed, if supersonic flights over populated areas become a common occurrence, the difficulties will become more rather than less apparent. Even a statutory scheme of compensation establishing strict liability for sonic boom damage would not eliminate the need to establish the causal relation. And the problem is one which is of concern to both plaintiffs and defendants. The good-faith plaintiff will face the difficulties noted above. And as supersonic flights become more frequent and recovery for boom-damage more possible, the threat of bogus claims will become increasingly real. This threat may be aggravated by the substantial possibility that the public's reaction to sonic booms will be adverse and will express itself in claims that stem more from heightened irritation and annoyance -- not monetarily compensable -- than from physical damage for which the law provides payment of compensation.[6]

The causation problem will remain an intractable one. Scientific data about whether claimed damage <u>could</u> have been caused by a boom or booms will become more helpful as reliable data is accumulated. But the question that will have to be answered in each and every case is whether the damage was <u>in fact</u> so caused. And, if the public reaction is as adverse as it appears that it may be, juries may turn out to be rather biased triers of the fact of causation.

That it will be difficult for plaintiffs in sonic boom cases to prove causation should not be taken to suggest that a burden of proving negative causation should be placed on the defendants. But the plaintiff should not be faced, in addition, with the burden of identifying the particular plane or

planes which cause the damage. A fair and workable means of solving the identity problem would be to establish a statutory entity that could be named as defendant in sonic boom damage cases and would be liable for all boom damage. All SST operators would be required to contribute to the entity in accordance with a formula which measures the risk of boom damage each creates. The formula might, for example, require contributions in proportion to the number of SST flights X $\frac{\text{total miles of flight}}{\text{total no. of flights}}$ X population under average flight carpet X normal overpressure of plane type at cruising speed and altitude.

2. The Role of Insurance

Because a number of suits have already been brought under insurance policies for claims of sonic boom damage, it seems appropriate to refer briefly to the role of insurance in this context. We express no view on whether any presently issued policy should be interpreted to apply to such damage. Present "all risk," "aircraft damage," or "explosion" clauses can be read to call for compensation for sonic boom damage.[7] The expectation is warranted, however, that the insurance companies will soon either specifically exclude coverage for sonic boom damage or specifically include it at an appropriately increased premium. If coverage is excluded, the property owners remain uncompensated. If it is included, the affected property owners as a group will still pay for the damage since they will bear the burden of increased premiums. No internalization of SST cost to the SST activity will be achieved. Thus, insurance fails to meet any of the objectives of an adequate compensatory scheme. Insurance, of course, can satisfy the purposes for which insurance is obtained: it spreads losses within a fairly homogeneous group of insureds. But insurance does not accomplish and should not be expected to accomplish a shifting of costs between the class of insureds and the class of SST users.

3. Theories of Recovery

There are several theories of liability under present law that could be resorted to with some hope of success to recover for sonic boom damage. We will examine them, in turn, primarily with reference to the suitability of each to achieve the basic objective of transfering efficiently to SST activity the costs of that activity when those costs manifest themselves as substantial losses falling initially on persons other than SST users.

(a) Negligence

In general, liability for negligence is based on the breach of a duty of the defendant to conform to a standard of conduct to protect others from unreasonable risks of harm.[8] Because it has been established that sonic booms can cause physical damage to property, one can argue persuasively that the standard of care which a prudent aviator must exercise is a high one.[9] Recovery based on the failure to observe even a high standard of care, however, would require the plaintiff not only to identify the responsible plane but also to trace the damaging effects of its boom to a particular negligent act, such as flying at too great a speed at too low an altitude or descending too rapidly at supersonic speed. The latter would be a very difficult task in view of the fact that factors other than flight maneuvers have an effect upon the intensity of the boom perceived at ground level. In particular, atmospheric variations can unpredictably but severely intensify the effect of any boom.

The doctrine of res ipsa loquitur may come to mind as a means of circumventing the difficulty of identifying a particular negligent act. This doctrine permits an inference of negligence when (1) the event causing damage is of a kind which ordinarily does not occur in the absence of negligence, (2) the event was caused by an instrumentality within the exclusive control of

the defendant, and (3) the damage was not due to a voluntary action on the part of the plaintiff.[10] With regard to the establishment of the first requirement, the argument has been made that, since every pilot knows that overpressures may cause damage and that improper flight procedures increase the likelihood of damaging overpressures, a pilot's failure to remain subsonic at low altitudes or during maneuvers is ordinarily negligence.[11] The argument makes sense as far as it goes, but it is not responsive either to the fact that the plaintiff may not be able to identify such maneuvers or to the fact that, because of atmospheric variations, damaging overpressures may be produced by supersonic flight which complies in every way with prescribed, prudent flight procedures. Because of these facts, a plaintiff seeking application of the res ipsa loquitur doctrine would have little hope of meeting the requirement calling for proof that the damage is of a kind which ordinarily does not occur in the absence of negligence. Indeed, one of the principal causes of concern over the sonic boom is that it appears to be a phenomenon which cannot be prevented by the exercise of any degree of care.

Plaintiff might attempt to ground a negligence case on the assertion not that any particular flight was negligent or that negligent flight maneuvers were conducted in the course of a particular flight but that any supersonic flight which creates shock waves which reach the ground in inhabited areas is negligent because it creates an unreasonable risk of harm to persons and property on the ground. But the flights of the SST, if they occur at all, will be authorized by and conducted in accordance with extensive regulations promulgated by the FAA in pursuance of its statutory duty and authority. For a court to hold supersonic flight unreasonable per se would require of it a determination that the regulations were unreasonable, and it seems fanciful

to assume that a court would so hold.[12] And although a plaintiff might argue that supersonic flight above populated areas is unreasonable, even when conducted in accordance with the strictest possible flight regulations, it is quite unlikely that a court could be persuaded to make such a finding, since it would amount to a judicial redetermination of an important issue of national policy, namely whether supersonic flight over land is appropriate.[13]

If we assume, however, that negligence is an appropriate theory of liability for sonic boom damages, we must then ask the question, with particular regard to the secondary effects of sonic boom such as personal injuries which may result from startle effects, whether the doctrine of "proximate cause" might be introduced by the defendant as a means of escaping liability for what he might term "unforeseeable consequences." There will be no attempt here to untangle the intricacies of the proximate cause doctrine. It suffices to note that the issue presented by the term is one of policy.[14] As a matter of policy, it is desirable that liability be imposed for the damaging secondary effects of sonic booms. While few would be able to predict the precise injury that might flow from any given startle reaction to a sonic boom, it does seem clear that supersonic flight creates a distinct and very real risk that a boom will occur and that damaging secondary effects will follow. Whether the plaintiff falls from a ladder while washing windows or cuts off his ear while shaving, his startle reaction cannot be regarded as unpredictable. This issue of proximate cause presently is regarded as a jury question and probably will continue to be so regarded. The problem thus becomes one of framing appropriate jury instructions.

(b) Trespass

Another theory that is frequently mentioned as having potential utility for sonic boom damage cases is trespass. Under modern trespass doctrine,

however, this theory is totally useless in the present context. Strict liability is no longer imposed, as it once was, merely by reason of the fact that a physical invasion has occurred. The plaintiff must show that the invasion was the result either of negligence, or of an activity of a type for which strict liability is imposed, or of an "intentional" act.[15] The limitations of the negligence theory have been pointed out above and the potential utility of a strict liability theory will be discussed below.[16] Thus, with the possible exception of "intentional" trespass, the term trespass is nothing more than a label attached to other theories of recovery to indicate that a physical invasion of some sort caused the harm.

To recover for an intentional trespass, plaintiff will have to show that the interference with his property was substantially certain to follow from defendant's voluntary act of supersonic flight;[17] proof that such flight created merely a risk of harm will not suffice.[18] If the damage to plaintiff's property was the result of an extraordinarily intense boom -- a "superboom" -- the defendant will argue that, although it was virtually certain statistically that a superboom would strike the ground somewhere along the flight path and that such a boom would cause some damage, it was far from certain -- the chances being about one in one-thousand -- that the superboom would strike plaintiff's property. On the other hand, if the plaintiff claims damage from an ordinary boom, he may be able to point to the substantial certainty that a boom with average strength would strike his property; but defendant would counter with the argument that such a boom would not be substantially certain to cause damage.

Some plaintiffs might prevail in trespass actions, but the theory itself seems an inappropriate and cumbersome means of dealing with sonic boom damage. One must conclude that recovery in trespass will stem more from the

notion that the plaintiff ought to recover than from a consistent application of the doctrine. It should be remembered that the "invasion" of the property and the interference with plaintiff's possession thereof will be accomplished not by the airplane itself -- which will not have flown directly over plaintiff's land nor below the 500 or 1000 foot minimum above which trespass by aircraft cannot occur because the airspace is in the public domain[19] -- but by the shock waves it produced. To term these shock waves the kind of "invasion" against which the trespass action is appropriate to protect seems a questionable distortion of language. There is precedent for such a holding however, in cases finding trespassory liability for the concussion effects of blasting.[20]

(c) Nuisance

Liability grounded on nuisance arises from a substantial and unreasonable non-trespassory invasion -- the result of an intentional, negligent, or abnormally dangerous activity -- of the plaintiff's interest in the private use and enjoyment of his land.[21] As a basis of liability for sonic boom damage it would be particularly appealing to plaintiffs whose principal complaint was the general and continuing annoyance and disruption of life's pattern that resulted from continuous exposure to booms.

Courts refuse to find nuisance liability where they determine that the utility of the defendant's conduct outweighs the gravity of the harm it causes to the plaintiff.[22] In purporting to make such a determination they are influenced by the fact of legislative authorization of the defendant's activity. According to the doctrine of legalized nuisance, they will not enjoin a legislatively sanctioned activity which would otherwise amount to a nuisance[23] and they are unlikely even to award damages.[24] Because granting relief in nuisance for sonic boom damages would require a court to

hold that defendant's conduct -- i.e., supersonic flight -- was unreasonable, it would call into question the appropriateness of the policy judgment permitting the flights at all; a court would, understandably, be unwilling to make such a finding.

(d) Strict Liability

The only basis of liability which seems fruitful as an avenue of recovery for sonic boom damages is strict liability. In Tentative Draft No. 10 of the Second Restatement of Torts, liability for damage to persons or property from abnormally dangerous activities is recognized.[25] The following factors are relevant in determining whether an activity is abnormally dangerous:

(a) whether the activity involves a high degree of risk of some harm to the person, land or chattels of others;

(b) whether the gravity of the harm which may result from it is likely to be great;

(c) whether the risk cannot be eliminated by the exercise of reasonable care;

(d) whether the activity is not a matter of common usage;

(e) whether the activity is inappropriate to the place where it is carried on; and

(f) the value of the activity to the community.[26]

It is clear that some of these factors are more applicable to SST operation than are others. For example, it seems to be true that, even if the average overpressure produced by a supersonic flight is within a generally non-damaging range of about 1.5 psf, factors such as wind velocity, temperature, terrain features, and humidity will cause one boom in a thousand to be twice as strong as the mean strength of booms in the flight track,[27] and the incremental effect

of these uncontrollable and essentially unpredictable factors upon the strength of the boom cannot be eliminated by the exercise of the utmost care. Thus the risk of harm from supersonic flight "cannot be eliminated by the exercise of reasonable care." Certainly SST flights will involve a high degree of risk of some harm to others: there will be some harm on every single flight over inhabited areas in view of the long stage lengths to which the SST will be limited. Whether the gravity of the harm that results is likely to be great is less certain. Very serious injury as a secondary consequence from startle effects will surely occur occasionally; we will not know the statistical probability until after the SST has been in operation for some time. The supersonic overflight experiments of the Air Force cannot be characterized as having caused grave harm; but those flights were limited in number and conducted with much smaller aircraft.[28] Whether the other Restatement factors are met is a highly subjective question.

In the Tentative Draft No. 10 of the Second Restatement of Torts, a distinction was sought to be taken between liability for ground or other damage from the flight of regular aircraft and that from the flight of "abnormally dangerous" aircraft, and only flight of the latter was to result in strict liability for damage.[29] A comment to the proposed section recognized that "ground damage from 'sonic booms' is a matter of strict liability."[30] The Institute rejected the proposed section, however, in favor of one which imposes strict liability for any ". . . harm to land, or to persons or chattels on the ground, . . . caused by the ascent, descent, or flight of any aircraft . . ."[31]

The argument has been made that strict liability for sonic boom damage can be based upon the fact that it is analogous to blasting, for the damaging

consequences of which most courts impose strict liability, holding it to be an abnormally dangerous activity when conducted in a populated area.[32] It is to those blasting cases involving concussion and vibration rather than those involving flying debris to which analogy is most apt. Most states apply absolute liability to both types of blasting cases, but a fading minority of four or five require minimal proof of negligence in the concussion-vibration cases.[33]

One must conclude that present law is unclear on whether strict liability will be imposed by the court for sonic boom damage. It is our conclusion that absolute liability is the best suited of presently recognized theories of recovery to accomplish the basic objectives that we have identified. Insofar as negligence, nuisance, and trespass actions require even minimal proof of "fault," they will permit some cases of serious damage actually caused by sonic booms to go unnoticed and uncompensated by the industry. Use of the fault concept is appropriate and compatible with the basic objectives of efficient use of resources and of fairness in adjusting involuntary income transfers to the extent, but only to the extent, that the law entertains a purpose to induce both of the reciprocally destructive forms of activity to take affirmative action to minimize losses. For example, if the aggregate cost of sonic boom damage could be lessened by the inexpensive installation of "sonic boom lightning rods" on all buildings, then the law should not remove all incentive for landowners to take that precaution. Fault concepts thus serve, in a crude way, the same basic function as the "pre-existing" - "subsequent" classification of property investments that was advocated in Part I of this report: by means of a highly judgmental jury process, the concept places some losses on each side and hence preserves some incentives for avoidance on each side. But we are unable to see any useful function to be served by requiring fault to be shown on the part of the SST operator. Damage on a substantial scale, and annoyance on a vast scale,

will flow from the decision, if it is made, to permit SST overflight of inhabited areas even if every flight is made with the utmost care. Even when there is carelessness involved, the plaintiff will generally be unable to prove it. The net consequence of application of the fault concept will be to leave on those damaged by booms the vast preponderance of the sonic boom costs of the SST activity. And no avoidance methods that might be adopted by prospective plaintiffs are readily apparent. To leave the costs on them rather than on SST users takes incentive to minimize costs from those who are in the better position to minimize and creates incentives where there is little that can be done to minimize. It results, moreover, in an income transfer in the form of reduced SST air fares to SST users, who will be well above the national mean in terms of affluence, from the population at large, who are the prospective plaintiffs.

Although there are not, at the present time, any apparent cost-minimizing steps that could be taken by persons exposed to sonic booms, one might think it desirable to anticipate the possibility that experience and resulting technological development may reveal the possibility of such steps. That anticipation could be achieved by reintroducing a fault concept <u>as a defense</u> to actions for sonic boom damage. The SST activity would be permitted to avoid absolute liability for damage caused by booms upon a showing that the plaintiff had acted unreasonably in failing to take generally known precautionary measures that would have reduced significantly the risk that the damage would result. Although we cannot imagine any appropriate applications of this defense at the present time, provision for the defense would allow the fault concept to play, at some time in the future, the only useful role it has.

C. Administrative Action.

It seems appropriate to emphasize at this point that a very large portion of the real social costs of supersonic air tranport will be left on those exposed to sonic booms even if a body of law is adopted that facilitates recovery for substantial boom damage whenever it occurs. For the major part of sonic boom costs will not take the form of discrete instances of substantial damage. Much of the cost will be in the form of millions of instances of trivial damage and hundreds of millions of instances of extreme annoyance. However favorable the law may be to recovery, it is expensive to bring law suits. Unless the damage suffered, discounted by the probabilities of obtaining a judgment, exceed the expense of litigation, suit will not be brought. All the cracked $5.00 window panes, all the dinner dishes dropped on kitchen floors as a consequence of startle reactions, all the millions of hours of sleep lost while comforting frightened children, the razor-nicked chins, the interrupted concerts, the hammered thumbs, the crest-fallen cakes and omelets -- all these will produce not litigation but at most a silent curse at the industry, at the FAA or at a society that seems to many to have confused technology with civilization. But all these are very real costs of supersonic flight, and failure to internalize them to that activity will mean that too many of society's scarce resources are being devoted to that activity -- more than would be so devoted in a perfectly structured society where all pains and pleasures could be tallied costlessly. There can be no genuine concern that too many costs are being imposed on the SST by liability law.

On the contrary, liability law may rectify most of the serious instances of inequity; but supplementary administrative action of a rigorous kind will

still be necessary to prevent uneconomically large devotion of resources to the SST. Basically this action may take either or both of two forms: (1) Imposition on the industry, through some system of taxation or assessment, costs in an amount corresponding to the estimated amount of social cost created by sonic boom but not internalized to the industry by liability law. (2) Directives to the industry that specific physical steps be taken to lessen boom exposure.

Early in this chapter we gave an example of the first type of measure: an excise tax scaled to the population exposed to booms by any particular SST flight and to the intensity of those booms. One general observation should be made about such cost imposition measures. They have a dual function: first, to create industry incentives to minimize boom costs by any technological measures useful to that end; second, to make SST transport more expensive to its ultimate consumers and thus reduce the quantity of such transport that they will demand. If the measure is to achieve these objectives, it must have certain characteristics. The costs must be levied in such a way that any individual airline can avoid them by conduct of the type the measure is intended to induce. For example, the X Airline Company should be able to reduce its tax obligation if it shifts a flight path from one over a populated coastal region to one over the adjoining ocean, or if it shifts from supersonic to subsonic aircraft between a particular city pair. Hence a tax on gross revenues of, or on all fuel consumed by, airlines that operated both subsonic and supersonic craft would be wholly inappropriate. And a flat charge per SST flight would be less desirable than a tax such as we have suggested, since a flat charge would fail to take into account population exposure and boom intensity.

Finally the measure should be devised to assure that the costs imposed, insofar as they cannot be avoided by preventive measures, are passed on through

higher fares to customers who choose SST flights in preference to subsonic flights. Effective intermodal competition between SST's and subsonic aircraft must be maintained. In terms of our present national transportation policy, an "inherent advantage" of subsonic planes is that they do not cause booms. It is vital to sound air transport policy that this inherent cost advantage be preserved and passed on to subsonic customers. Under no circumstances should the Civil Aeronautics Board be permitted to yield to the temptation to increase or fail to reduce subsonic fares, and to hold SST fares at a low level, in order to improve the relative attractiveness of SST flight. It is quite probable that the Board will be subjected to pressure to take this step, both by airlines that have sunk investments in SST programs and by government officials who are seeking to assure that government investment in SST development is repaid and to minimize the risk that governmental encouragement of the SST program will be publicly exposed as an error of monstrous dimensions. Subsonic air transport should never be required to subsidize the real social costs of the SST. Toleration of such a fare structure would directly undermine the cost imposition measures we have been discussing.

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We turn to the second basic type of administrative action: governmental requirement that specific physical steps be taken. Refusal by the FAA to certify aircraft that generate normal overpressures in excess of specified limits is the obvious example. Requirements that particular technological advances be adopted, that particular routes be followed or that particular maneuvers be avoided all fall under this heading. For convenience we will refer to measures of this type as "certification."

It should be understood that cost imposition and certification are complementary forms of administrative action. If either were done with omniscience and perfect implementation, the other would be unnecessary. And the results would be precisely the same in all respects whether the first was

so executed and the second abandoned or the second so executed and the first abandoned. In practice neither can be so executed, and the best obtainable results probably can be achieved by doing imperfectly a little of each.

Certification obviously will impose costs on the industry. If no cost imposition measures were taken, optimum results would be obtained by imposing more and more certification measures until the aggregate of costs they imposed was just equal to the social costs of the SST that were not being internalized by liability law. If only half the costs left external by liability law are imposed by certification, the remaining half should be imposed by cost imposition. Of course this nice theoretical symmetry only applies if the certification measures are precisely the best ones. In an imperfect world, they will not be; but the theoretical relationship is, nevertheless, a rough guide to policy formation.

If we could be freed of all political constraints, our choice would be to abandon certification completely and pursue a vigorous policy of cost imposition. The industry is the best source of information as to what physical steps will yield the least amount of boom per dollar expended. High administrative costs are involved in getting that information out of the industry and into the FAA so that the FAA can then tell the industry what to do. Moreover, under a certification policy the industry has no incentive to generate information, so less will exist to be extracted. A vigorous cost imposition policy, one that imposed at least 100 percent of external cost and imposed it in proportion to boom exposure and intensity, would make it profitable for the industry to generate information and take the right physical steps voluntarily.

But passing excise taxes lacks the political glamour of asking brusque questions and then giving brusque orders. We assume that a vigorous cost imposition policy is not politically feasible and that certification must be resorted to at least in part.

As to what certification measures should be adopted, we have no opinion.

D. Recommendations.

Our recommendations regarding the sonic boom problem, in summary, are as follows:

a) To eliminate impossible problems of identifying boom-producing aircraft, and to eliminate difficult problems of service of process and venue with respect to all of the airlines whose planes might have caused a particular boom, federal legislation should be passed creating an entity, hereafter called a Statutory Fund, which may be served in any state and with respect to which venue is proper at the residence of the plaintiff and wherever the damage occurred. The Statutory Fund should be subject to suit in state as well as in federal courts.

b) The Statutory Fund should be strictly liable for all damage proved to have been caused by any sonic boom. It should be a defense to any claim that the plaintiff unreasonably failed to take precautionary measures that would have avoided the damage.

c) Every SST operator should be required from time to time to contribute to the Fund in proportion to the number of persons it exposed to booms during the prior accounting period multiplied by the normal overpressures of its booms. The aggregate of contributions should be adequate to keep the Fund solvent after paying all judgments, litigation expenses, and the levy described in paragraph (e). The Fund should have no function other than to settle and litigate claims.

d) The Fund shall be required to pay litigation expenses of plaintiffs to the following extent: Of the plaintiff's total expenses, the trial judge may disallow any that he finds to be unreasonable. Of those that the trial judge allows, the Fund should pay a proportion equal to the ratio between the damages awarded and the damages alleged in the complaint.

e) The Department of Health, Education and Welfare should estimate, during each calendar year, the extent to which costs were imposed on the population of the United States during the prior year in excess of the disbursements of the Fund for damage and litigation expenses during that year. The Fund should then pay into the United States Treasury the amount of that estimation.

f) The CAB should be directed by statute that, in setting SST fares and subsonic fares, it should preserve the inherent cost advantages of subsonic flight.

Part II

Footnotes - Chapter I

1. Since the air is three-dimensional, the sound wave expands in the form of a sphere rather than the circular form of the water wave.

2. The speed of travel of a shock wave is actually slightly faster than that of a sound wave.

3. This is true even for a shock produced by a plane travelling at Mach 1.5 and 40,000 feet altitude. Walker & Doak, Effects of Ground Reflection on the Shapes of Sonic Bangs, 5e *Congrés International d'Acoustique* (Belgium 1965).

4. However, the exact overpressure configuration for an explosion does differ from that of a sonic boom.

5. The shock wave strength depends most directly upon the lift rather than the weight, but the lift is a function of the weight. See Thompson & Parness, Sonic Boom and the SST, 39 *Aircraft Engineering* 14 (March 1967); Hutchinson, Defining the Sonic Boom Problem, 1 *Aeronautics & Aerospace Engineering* 55 (Dec. 1963).

6. At supersonic speeds the primary source of air agitation is the airplane surface cutting through the air and not the hot gases from the engines. At subsonic speeds, these hot gases are the primary source of the noise with which we are all familiar.

7. Friedman, et al., Effects of Atmosphere and Aircraft Motion on the Location and Intensity of a Sonic Boom, 1 A.I.A.A. Journal 1327 (1963).

8. Latest drawings set the length at 290 feet and the weight at 575,000 pounds for the transcontinental and 675,000 pounds for the transoceanic versions.

9. At 70,000 feet, the speed of sound is between 660 and 680 mph. See Hohenhemser, The Supersonic Transport, 8 Scientist & Citizen 1 (April 1966); Albright, Physical Meteorology (New York 1941).

10. Hilton, Sonic Boom Measurement during Bomber Training Operations in the Chicago Area, NASA Technical Note D-3655 (Oct. 1966).

11. This combination is a result of the thermodynamic properties of air. As the front wave creates a region of higher pressure, the temperature in the region of higher pressure rises above the temperature of the background air. Therefore, the shock wave traveling in the increased pressure region moves faster than the front wave and catches up with it after a sufficient distance of travel.

12. The region before combination is known as "near field" and the region after combination is knows as "far field".

13. From comments of Maynard Pennell, Boeing Vice President and director of the SST program, as reported in 86 Aviation Week 38 (Jan. 16, 1967).

14. The increase in operating cost over the most efficient fuel utilizing configuration is about 10%. See Thompson & Parnell, supra note 5.

15. For the supersonic transport, this width is generally considered to be two to three times the altitude of the plane (measured from cut-off to the line of flight).

16. Figure 13 was derived from Kane, Some Effects of the Nonuniform Atmosphere on the Propagation of Sonic Booms, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965).

17. The conical form pertains only to shock waves produced by an object moving at a constant speed through a uniform medium.

18. Above 35,000 feet to well above 70,000 feet the temperature remains at an average of -70° F. See Albright, supra note 9.

19. The velocity of a shock wave is closely dependent upon the velocity of sound. The velocity of sound, and hence a close approximation of shock wave velocity, in a gas (such as the atmosphere) can be expressed by the following formulae.

Where P_o is the ambient pressure, P is the pressure at shock wave peak, and γ is a constant for the gas equal to the ratio between the specific heats of the gas mixture $(\gamma = {}^{C}P/C_v)$:

$$V\ \text{shock} \approx V\ \text{sound} \left\{ 1 + \frac{\gamma + 1}{4\gamma} \left(\frac{P - P_o}{P_o} \right) \right\}$$

But $V\ \text{sound} \propto \sqrt{\frac{P}{\rho}}$ where ρ equals density; and since ρ is very nearly proportional to P, the dependence on pressure is very slight.

However, $\rho \propto \frac{1}{T}$, and therefore V sound $\propto \sqrt{T}$, resulting in the extreme temperature effect described in the text. See Friedman, supra note 7.

20. In order for the shock wave to be deflected from reaching the ground for the SST, the plane must climb at an angle greater than 40°, which could only be possible for a small portion of the flight, and which would probably not be within the capability of the SST without a substantial extra cost in design and operation.

21. United States Standard Atmosphere (NASA, Air Force & Weather Bureau 1962).

22. See Friedman, A Description of a Computer Program for the Study of Atmospheric Effects on Sonic Booms (NASA CR-157, 1965).

23. Pure acoustic theory when applied here may give substantially higher overpressure values at the focus point than really exist. A shock wave normally involves a strong disturbance of the air, and a tendency toward equilibrium condition at the focus will prevent sharp discontinuities along the wave front.

24. See Friedman, supra note 22. For a case in which the temperature fell from standard temperature at 5,000 feet to 25°F. on the ground (compared to about 50° for standard), the overpressure was 15 per cent higher than if the standard atmospheric condition prevailed in the same air region. (This was computed for a shock wave with 0.75 psf overpressure in standard conditions).

25. See Friedman, supra note 22.

26. *See* Friedman, *supra* note 22; Kane, *supra* note 16; Dressler, *Sonic Boom Waves in Strong Winds*, FFA Report 97 (Stockholm, 1964).

27. *See* Friedman, *supra* note 22.

28. Hilton, *et al.*, *Sonic Boom Measurements During Bomber Training Operations in the Chicago Area.* (NASA Technical Note D-3655, 1966). This test involved level flight and the sensing devices were not situated where they could detect the acceleration focus, so possible maneuver magnifications could not have been included in the experimental results.

29. *See* Lundberg, *The Menace of the Sonic Boom to Society and Civil Aviation*, FFA Memo PE-19 (Stockholm, 1966). Hilton says that the highest actual overpressure measured by the sensing devices in Oklahoma City was 1.4 times the calculated overpressures.

30. *See* Maglieri, *Some Effects of Airplane Operations and the Atmosphere on Sonic Boom Signatures*, *in Symposium on Sonic Boom*, 39 Acoustical Soc. Amer. J. (1965).

31. *See ibid.*

32. A recent study has shown that if a plane accelerates around the curved path, the acceleration and curvature may be made to balance so that no focus is produced. However, practically speaking, such a balancing effect is relevant only to fighter aircraft which make strong accelerations and sharp turns. *See* Friedman, *supra* note 22.

33. It is very difficult to determine experimentally the maximum magnifications which can be expected from combinations of maneuver and atmospheric effects, since the effects will be relatively localized and can be predicted to fall only within a large area. Therefore a huge grid of closely spaced measuring devices is necessary to record adequately the possible combinations of magnifications. (For example, an area five miles square with a device every 200 feet square would require 16,000 devices). This is why the theoretical approach has been emphasized here. Of course, the use of theory is not the same thing as mere speculation, for these theories are well founded upon many years of experience with shock waves and adequately represent their behavior.

Even the scanty recordings from experiments conducted with Air Force planes over Chicago, St. Louis, and Edwards Air Force Base indicate that shock waves twice the ordinary strength occur at least 0.1% of the time. See Hilton, supra note 10. This means that in one supersonic run from Los Angeles to New York, at least 100 square miles of territory will be affected by doubly strong shock waves. These estimates may be conservative, since none of the tests involved adverse maneuvers like those required from the SST, relatively few runs were made (e.g. 22 in Chicago), and few sensing devices were utilized.

34. See Warren, Experience in the United Kingdom on the Effects of Sonic Bangs, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965).

35. The figures showing reflections have been simplified for illustration purposes. The shock waves do not actually break into separate pieces. The principal reflection products are connected by a continuous band

which has less strength than the principal portions shown. As the distance from the point of the reflection is increased, the stronger portions of the reflected wave tend to even out with the less strong portions, forming a uniform wave of reduced strength.

36. Shock waves striking the ground at shallow angles near the grazing angle are also reflected more efficiently and from more types of surfaces than shock waves striking at larger angles. An addition high in the air can strike passing aircraft, but none of the shock waves are likely to affect an aircraft because of its sturdy design. See Hubbard, Nature of the Sonic Boom Problem, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965).

37. FAA minimum standards have been set at 1.5 psf for cruise and 2.0 psf during climb. The British Concorde is projected to have lower average overpressures because it is a smaller, lighter plane and will travel at a lower speed than the American SST. See Thompson & Parnell, supra note 2.

38. See Comments of Maynard Pennel, the Boeing SST director, supra note 13.

39. The measurement of the overpressures was made at practically the same location as the affected object, so the localized shock wave was measured.

40. See Boom in a Ghost Town, Business Week, Dec. 12, 1964, p. 29; Effects of Sonic Booms on Buildings, 4 Materials Research & Standards 582 (1964).

41. An example of the destructive force of a sonic boom produced at low altitudes occurred in Ottawa, Canada when an F-104 fighter broke the sound barrier while flying some 500 feet above the new Ottawa air terminal. All the windows on one side were smashed, and the roofing was ripped significantly. Fortunately there were no serious injuries to persons, since the terminal had not yet opened for general use. See Effects of Sonic Booms on Buildings, 4 Materials Research & Standards 582 (1964).

42. Hohenemser, The Supersonic Transport, 8 Scientist & Citizen 1 (Apr. 1966). For an interesting article concerning fatigue in aircraft structures, see Trapp & Forney, A Review of Acoustical Fatigue, in Fatigue--An Interdisciplinary Approach (Syracuse U. Press 1964).

43. von Gierke, Effects of Sonic Boom on People: Review and Outlook, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965).

44. A three-fold increase in frequency is the equivalent of a two-fold increase in pressure with regard to loudness. See Warren, supra note 32.

45. One estimate places the average for present day fighters at 17 cps and for the SST at 1.7 cps.

46. See Broadbent & Robinson, Subjective Measurements of the Relative Annoyance of Simulated Sonic Bangs and Aircraft Noise, 1 J. Sound & Vibration 162 (1964).

47. See Kryter, Laboratory Tests of Physiological Psychological Reactions to Sonic Booms, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965); Kryter, Psychological Reactions to Aircraft Noise, 151 Science 1346 (1966).

48. See Kryter & Pearson, Laboratory Tests of Subjective Reactions to Sonic Booms, (NASA CR-187, 1965).

49. These include tests over St. Louis in 1961-2 (53 flights in 4 months), Oklahoma City in 1964 (1253 flights in 6 months), and Chicago in 1965 (22 flights in 2 months).

50. One complaint per 63,000 person-exposures was received in Oklahoma City (a total of 12,500 complaints in 6 months). At this ratio, each transcontinental SST flight would result in about 150 official complaints.

51. See Nixon & Borsky, Effects of Sonic Boom on People: St. Louis, Missouri 1961-1962, in Symposium on Sonic Boom, 39 Acoustical Soc. Amer. J. (1965).

52. See Sonic Booms of SST May Prove Unacceptable to 25% of People Affected, 74 S.A.E. Journal 88 (June 1966).

53. If everyone affected by the test had a most favorable attitude, the 8% would represent 48,000 people. Comparable figures for persons with least favorable attitudes are 43% and 258,000.

54. See The Sonic Boom Comes Home, 2 Astronautics & Aeronautics 70 (Sept. 1964).

55. See Stanford Research Institute, Report on Data Retrieval and Analysis of USAF Sonic Boom Claims Files 84-85 (1967) (hereinafter cited as SRI Report).

56. See SRI Report 84-87. The SRI Report indicates that, although the number of claims for damage to animals is small relative to the number of claims for damage to structures, the average amount paid per claim for animal damage is significantly higher than that paid per claim for structural damage: $775 for damage to animals as opposed to $102 for damage to structures.

57. This analysis uses the same method, but more conservative figures as that used by Lundberg in The Menace of the Sonic Boom to Society and Civil Aviation, FFA Memo PE-19 (Stockholm, 1966).

Part II

Footnotes - Chapter 2

1. The flight paths most likely to produce sonic booms which will effect the Quincy area include those connecting the eastern metropolitan areas of Boston, New York, Philadelphia, and Washington, D.C., with the western metropolitan areas of Denver, San Francisco, and Los Angeles, in addition to the two paths connecting Los Angeles with Detroit. Typical figures used to compute the estimate include the following number of daily flights in one direction: one flight from Denver to Philadelphia, five flights from San Francisco to Washington, D.C., and ten flights from Los Angeles to New York. According to presently authorized routes, at least American Airlines, United Airlines, Continental Airlines and Trans World Airlines would be users of these flight paths. Moody, Transportation Manual (Sept. 1965).

2. See Tabb v. United States, 10 Av. Cas. 17410 (D.Ga. 1965); Dabney v. United States, 249 F. Supp. 599 (D.N.C. 1965); Brown v. United States, 230 F. Supp. 774 (D. Mass. 1964).

3. See Comment, Sonic Booms - Ground Damage - Theories of Recovery, 32 J. Air L. & Com. 596, 597 (1966).

4. See Summers v. Tice, 33 Cal.2d 80, 199 P.2d 1 (1948), which enunciates the doctrine that plaintiff must not be denied recovery merely because he cannot identify which of two defendants actually caused the damage. Each defendant was equally likely to have caused the damage

and one of them surely did; they were held jointly and severally liable since neither could disprove his responsibility.

5. See *Restatement (Second), Torts* § 433 B (1965).

6. See the district judge's remarks about the plaintiffs in Coxsey v. Hallaby, 231 F. Supp. 978, 980 (W.D. Okla. 1964).

7. See Varner, *Legal Aspects of the Sonic Boom* 23 *Ala. Law.* 342, 246-50 (1962); Comment, 32 *J. Air L. & Com.* 596, 598-601 (1966). Absent specific exclusionary language, recovery under an "all risk" policy would surely be available. And one court has granted recovery under an aircraft damage clause in spite of the fact that the policy stipulated that "loss by aircraft shall include direct loss by . . . objects falling therefrom." Alexander v. Fireman's Ins. Co., 317 S.W.2d 752 (Tex. Civ. App. 1959). The two cases in which recovery for sonic boom damage under an explosion clause has been considered have denied the possibility of recovery. *Id.*; Bear Bros., Inc. v. Fidelity & Guar. Ins. Underwriters, 6 Av. Cas. 17497 (Ala. Cir. Ct. 1959). There is general agreement among the experts that a sonic boom is a pressure or shock wave accompanied by a noise. Thus it would appear that a jury could conclude that a sonic boom comes within the definition of "explosion" when that word is given its plain meaning according to the common experience of ordinary men.

8. *Prosser, Torts* 146 (1964 ed.).

9. Comment, 32 *J. Air L. & Com.* at 601.

10. *Prosser, Torts* 218 (1964 ed.).

11. Comment, 32 *J. Air L. & Com.* at 602.

12. *Cf.* Boyce Motor Lines, Inc. v. United States, 342 U.S. 337 (1952).

13. *But see* Neher v. United States, No. 3-64-Civil 149 (D. Minn. Jan. 13, 1967) (memorandum decision). The court held the United States negligent in designating and using a military supersonic flight corridor over the heavily populated Minneapolis-St. Paul area.

14. *See generally* Prosser, *Torts* 282-330 (1964 ed.).

15. *Restatement (Second), Torts* § 158 (1965).

16. *See* text accompanying notes 25-33, *infra*.

17. A trespass to chattels or a conversion action as a means of recovering for damage to particular items would also require that plaintiff prove that the alleged harm was a substantially certain result of supersonic flight.

18. Prosser, *Torts* 32 (1964 ed.); *Restatement (Second), Torts* § 8A (1965).

19. 49 *U.S.C.* §§ 1301(24), 1304 (1964).

20. *See, e.g.*, Adams & Sullivan v. Sengel, 177 Ky. 535, 197 S.W. 974 (1917).

21. *Restatement, Torts* § 822 (1938).

22. *Ibid.* § 826.

23. See Loma Portal Civic Club v. American Airl., Inc., 61 Cal.2d 582, 394 P.2d 548 (1964).

24. With regard to the comparable situation of noise at public airports, only one recent case specifically acknowledges the existence of a nuisance cause of action against a municipal airport operator. Chronister v. City of Atlanta, 99 Ga. App. 447,.108 S.E.2d 731 (1959).

25. Restatement (Second), Torts § 519 (Tent. Draft No. 10, 1964).

26. Id. at § 520.

27. Comment, 32 J. Air L. & Com. at 603.

28. See SRI Report 11, which indicates that the weighed average of paid claims was only $72 in the controlled programs of flight over Chicago, Pittsburgh, Milwaukee, St. Louis, and Oklahoma City.

29. Restatement (Second), Torts § 520A (Tent. Draft No. 10, 1964).

30. Restatement (Second), Torts § 520A, Comment d at 76 (Tent. Draft No. 10, 1964).

31. Restatement (Second), Torts § 520A (Tent. Draft No. 12, 1966). In 1922, the Commissioners on Uniform State Laws promulgated a Uniform State Law of Aeronautics, section 4 and 5 of which imposed strict liability for ground damage upon both the owner and the operator of the aircraft. Note, Federal Liability for Sonic Boom Damage, 31 So. Cal. L. Rev. 259, 269 (1958). The Act was not well received by the

state legislatures, and the Commissioners withdrew it; they have not submitted a revision. Decisional law, however, has been to the effect that the airplane is not an inherently dangerous instrument when operated by a competent pilot exercising reasonable care. See, e.g., Johnson v. Central Aviation Corp., 103 Cal. App. 2d 1022, 229 P.2d 114 (1951).

32. See, e.g., Adams & Sullivan v. Sengel, 177 Ky. 535, 197 S.W. 974 (1917).

33. See generally Comment, Burden of Proving Negligence in Non-Trespass Blasting Cases Lightened, 30 Fordham L. Rev. 544 (1962).